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Addressing challenges in vector control: a review of current strategies and the imperative for novel tools in India's combat against vector-borne diseases

Gaurav Kumar [1], Rajendra Baharia,[2] Kuldeep Singh,[1] Sanjeev Kumar Gupta,[1] Sam Joy,[3] Amit Sharma [1,4] Manju Rahi [1,3,5]

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[1]ICMR-National Institute of Malaria Research, New Delhi, Delhi, India
[2]ICMR-National Institute of Malaria Research Field Unit, Nadiad, Gujarat, India
[3]Indian Council of Medical Reseach, New Delhi, India
[4]Molecular Medicine, International Centre For Genetic Engineering and Biotechnology New Delhi, New Delhi, India
[5]Indian Council of Medical Research -Vector Control Research Centre, Puducherry, India

Correspondence to
Dr Manju Rahi;
drmanjurahi@gmail.com

ABSTRACT

Vector-borne diseases (VBDs) exert a substantial burden across the world, especially in tropical countries. Malaria, chikungunya, dengue, visceral leishmaniasis, lymphatic filariasis and Japanese encephalitis are among the public health concerns for India. One of the major pillars for the containment of VBDs is vector control and different tools have been employed for several decades. These range from chemical insecticides used in indoor residual sprays, space sprays, fogging, treated bednets and larvicides to biological control methods such as larvivorus fishes and environmental control and modification measures such as source reduction. However, these methods are increasingly becoming less effective due to several reasons such as insecticide resistance, outdoor biting, behavioural changes in vectors for biting and resting, climate change, movement of population, vector incursion to newer areas and others. It is essential to develop and test new tools for vector control to surmount these challenges. Though focusing on India's public health concerns, the new tools enumerated here can be tested by any country with similar epidemiological and environmental conditions. The promising new vector control tools are insecticide-treated nets with synergist and/or pyrrole chlorfenapyr, alternatives/additions to synthetic pyrethroids like neonicotinoids, clothianidin for indoor residual spray, newer formulations such as *Bacillus sphaericus* for use in larvicides, attractive toxic sugar baits, especially to curtail outdoor transmission, endectocides like ivermectin for use in animals/humans, insecticidal paints, spatial repellents, insecticide-treated wearables and others. Genetic modification technologies (Sterile Insect Technique/Incompatible Insect Technique/Wolbachia transfection) are also upcoming strategies. Among the six VBDs, India is committed to the elimination of three (malaria, visceral leishmaniasis and lymphatic filariasis) and it will require additional and/or novel tools to overcome the roadblocks in our current journey to the goal of control/elimination of these VBDs.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Vector-borne diseases (VBD) pose a significant burden in tropical countries, including India, with diseases such as malaria, dengue, chikungunya, visceral leishmaniasis, lymphatic filariasis and Japanese encephalitis being of particular concern.
⇒ Vector control has been a key strategy for disease containment, relying on various methods such as chemical insecticides, bed nets, larvicides and environmental modifications.
⇒ Several new vector control tools have been developed or tested in countries including India.
⇒ India is committed to elimination of three VBDs (malaria, visceral leishmaniasis and lymphatic filariasis), highlighting the urgency for additional or novel tools to overcome the existing barriers and achieve the goal of control or elimination of these diseases.

INTRODUCTION

Vector bone diseases (VBDs), which are spread through the infected bite of arthropods, accounted for ~17% of the global burden of communicable diseases and put ~80% of global population at risk of their infection.[1] VBDs such as African trypanosomiasis, Chagas disease, dengue, leishmaniasis, malaria and schistosomiasis are responsible for over one billion cases, subsequently causing one million deaths each year.[2] In India, malaria, dengue, chikungunya, visceral leishmaniasis (kala-azar), Japanese encephalitis (JE) and lymphatic filariasis (LF) are the major VBDs that present a risk to a large proportion of its vast population. In the WHO's South East Asia region, India contributed the highest number of estimated malaria cases (79%).[3] Malaria presents a significant burden in terms of both morbidity and mortality in India, with approximately 698 million people at risk across 747 districts. India reported 0.17 million cases of malaria in 2022 as per national malaria programme. Furthermore, India accounts for around 34% of worldwide dengue cases, with 193 245 reported cases in the year 2021. Chikungunya

WHAT THIS STUDY ADDS

⇒ This study adds valuable insights into the need for new vector control tools in the Indian context.
⇒ It highlights the challenges faced by the national VBD control programme, such as insecticide resistance, changes in vector behaviour, and the impact of climate change.
⇒ By discussing the prospects, feasibility, and availability of new vector control tools, the study provides a comprehensive guide for the programme to incorporate innovative strategies to effectively control and eliminate vector-borne disease (VBDs) in India.
⇒ The findings of this study contribute to the ongoing efforts to improve public health outcomes and address the urgent need for more sustainable and efficient vector control measures.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Policymakers can utilize this study to recognize the urgent need for additional resources and support for the development, testing, and adoption of new vector control tools to enhance the effectiveness of VBD control and elimination programmes at a national level.
⇒ The study's findings can inform the design and implementation of vector control strategies in practice, guiding public health programmes to incorporate innovative tools that address the challenges posed by insecticide resistance, changes in vector behaviour, and other factors.
⇒ The identification and enumeration of promising new vector control tools, such as insecticide-treated nets with synergists, neonicotinoids, attractive toxic sugar baits, and genetic modification technologies, provide valuable directions for future research and development efforts.

has witnessed a striking surge in recent years, escalating from 3300 cases in 2015 to 11 890 cases in 2021. Kala-azar disease, endemic across four states, that is, Bihar, Uttar Pradesh, Jharkhand and West Bengal of the country, caused 1276 cases and 28 deaths in 2021. LF is endemic in 257 districts in 21 states and union territories. In 2021, the country recorded 525 440 lymphoedema and 144 645 hydrocele cases. Telangana and Jharkhand states bear a major brunt of morbidity due to LF.[4]

The geographical spread and the vectors responsible for these diseases are depicted in figure 1. India is committed to elimination of malaria and LF by the year 2030 and visceral leishmaniasis by 2024. In addition, national programme is also concerned with the control of dengue, chikungunya and JE. Vector control is a key component of any disease elimination or control strategy. An integrated control programme, including vector control operations, assisted by modern tools for real time surveillance and data collation would be supportive in elimination or control of these diseases.[5 6] Vector control strategies include the use of biological control agents, chemical insecticides and environmental management. Current vector control tools and strategies employed in India are described in online supplemental appendix. Vector control is one of the key components essential for protecting vulnerable communities such as children and pregnant woman who may be more susceptible to severe outcomes of vector borne diseases due to biological and non-biological (social) reasons. It aims to prevent the transmission of VBDs, reducing morbidity and mortality and promoting overall well-being. Vector control measures can also assist in containing outbreaks by suddenly crashing the vector population and bringing a halt to the onward transmission. While vector control is crucial in the prevention and control VBDs, its success is marred by challenges, which include the development of resistance to insecticides, environmental concerns, limited resources, poor or inadequate usage by the community and changes in vector behaviour rendering existing methods ineffective. Addressing these challenges requires a multifaceted approach that involves innovative technologies, sustainable interventions, community engagement, adequate funding and new tools in vector control. The deployment of novel and innovative tools and strategies in vector control has the potential to enhance the effectiveness and sustainability of vector management. In this review article, we have tried to discuss the challenges faced by the current vector control tools employed in the Indian public health programme and possible new tools for deployment. The information on novel tools was sourced from PubMed and Google scholar search engines for articles. The search terms employed included key terms such as mosquito vector, vector control, new vector control tools, novel vector control tool. Furthermore, relevant articles were identified through cross-referencing to ensure a thorough examination of the literature. The study encompassed book chapters, annual reports and research conducted in India and outside. However, research articles in languages other than English were not included in the present work.

THE CHALLENGES AND NEED FOR NEW VECTOR TOOLS

National Center for Vector Borne Diseases Control (NCVBDC), under Indian Ministry of Health and Family Welfare has a wide array of options available for vector control for the VBDs. The total reliance on dichloro diphenyl trichloroethane (DDT) for malaria control during the eradication campaigns of the 1970s and 1980s and its subsequent failure resulted in the reversal of progress made in controlling the disease. Learning from history, we should identify the challenges to the currently available methods and strategically choose, develop and adopt the most appropriate novel vector tools. The challenges that India may encounter in its plans to eliminate or control VBDs are listed in table 1 and briefly described below:

Insecticide resistance

The development of resistance in mosquitoes against the present choices of insecticides is one of the major factors, which demands new tools. Two primary malaria vectors, namely *Anopheles culicifacies* and *An. stephensi* have demonstrated a varying degree of resistance to all three

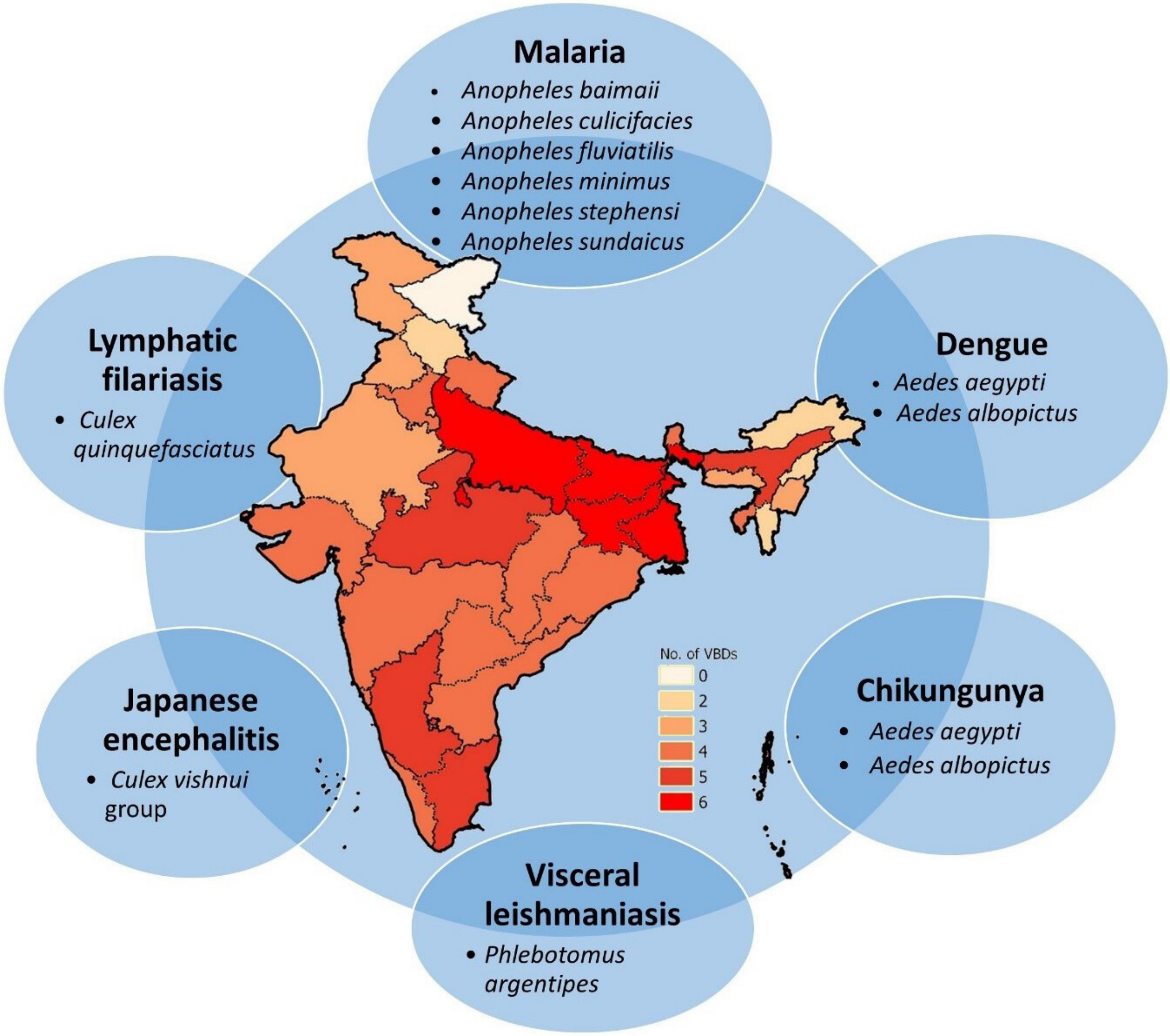

Figure 1 Vectors and state-wise presence of multiple vector borne diseases in India.

insecticide classes, namely DDT, malathion and synthetic pyrethroids.[7–9]

In our study on insecticide susceptibility status of malaria vectors in India revealed that the primary vector, *An. culicifacies*, exhibited resistance to public health insecticides, including DDT in 52 study districts across nine states, and demonstrated resistance or possible resistance to malathion and synthetic pyrethroids in over 80% of the districts examined.[9] Similarly, in another study, primary malaria vectors like *A. stephensi* and *A. fluviatilis* have been found resistant to DDT in eight states of the country.[8]

Vectors of chikungunya and dengue, that is, *Aedes aegypti* and *Ae. albopictus* were found to be resistant against DDT, but susceptible to synthetic pyrethroids.[10 11] Kala-azar vector *Phlebotomus argentipes* has also been reported to be DDT resistant.[12 13] As a result, NCVBDC recommended the use of synthetic pyrethroids in (Indoor Residual Spray (IRS) for the control of *Plasmodium argentipes* in 2015.[14] There is lack of comprehensive data on insecticide resistance in LF and JE vectors in the country. Insecticide resistance shown in these studies revealed the diminishing impact of vector control in six major VBDs in India.

Outdoor biting of vectors

While the majority of Indian malaria vectors exhibit endophagic behaviour, there have been reported instances of outdoor biting by *An. baimaii* in Tripura.[15] The possible reason for such a change in vector biting behaviour has been hypothesised as prolonged use of long lasting insecticidal nets (LLINs) and IRS with chemical insecticides, potentially driving mosquitoes to feed outdoors. There is currently a lack of available vector control tools within public health programme for outdoor biting vectors. Vectors of JE *Culex vishnui* and *Cx. tritaeneoyhynchus* feed indoors as well as outdoors.[16 17] Additionally, it is worth noting that monitoring for outdoor biting behaviour has not been carried out adequately, hence the extent of this phenomenon remains unknown.

Change in vector behaviour

The emergence of behavioural changes in malaria-transmitting mosquitoes poses a significant challenge to

Table 1 Challenges for vector control and recommended novel vector control tools

Number	Challenges	Recommended novel vector control tools
1.	Insecticide resistance	► New insecticides ► New generation insecticide-treated nets ► Attractive Toxic Sugar Bait (ATSB) ► Endectocides ► Insecticide paints with novel compounds
2.	Outdoor biting	► Insecticide-treated materials/wearables ► Spatial repellents
3.	Change in vector behaviour	► Insecticide-treated materials/wearables ► Spatial repellents ► Animal shelters targeted vector control ► Mosquito traps
4.	Human behaviour and practices	► Insecticide-treated materials ► Spatial repellents ► ATSB
5.	Newer vectors or vector incursion	► Long lasting formulations of larvicides ► ATSB
6.	Migratory or vulnerable populations	► Insecticide-treated materials/wearables ► Spatial repellents ► Mosquito traps
7.	Logistic issues/lack of human resources	► Drones ► Long lasting formulation of insecticides ► Insecticide paint
8.	Climate change	► Long lasting formulations of insecticides ► ATSB ► Spatial repellents

the effectiveness of existing interventions using IRS and LLIN, potentially undermining the progress made in malaria transmission control.[18] Notably, in Odisha, a shift in resting behaviour of *An. fluviatilis* has been observed, with a predominant presence in mixed dwellings with high anthropogenic nature.[19] Similarly, in Madhya Pradesh, outdoor resting behaviour of *An. culicifacies* has been reported, signifying a notable change in resting behaviour.[20] Such change in resting behaviour carry significant implications since current vector control tools target only endophilic vectors. Consequently, the absence of suitable tools tailored for mosquitoes, resting in different environments such as cattle shed or outdoors further exacerbates this challenge. This highlights the pressing need for the development of novel vector control strategies to effectively addressing this evolving scenario.

Cultural practices

Communities' cultural practices and behaviour are another set of challenges that necessitates new vector control tools. The northeast states of India have a considerable population involved in shifting cultivation, that is, slash and burn called Jhum cultivation.[21] Encroachment of *Jhumias* in virgin forest regions (which are mosquito genic and conducive for malaria transmission) for activities related to shifting agriculture exposes them to get malaria infections.[22] Galagan *et al* reported that Jhum cultivators were at higher risk of acquiring malaria infection compared with those who did not practice Jhum cultivation.[23]

Newer vectors or vector incursion

There are reports that mosquito vectors are invading newer areas and expanding their geographical range. *An. stephensi*, an Indian urban malarial vector, has invaded Sri Lanka and is a cause of concern for the country, which has achieved malaria elimination in 2016.[24] Expansion of *An. stephensi* has been reported from various African countries during the last decade—Djibouti (2012), Ethiopia and Sudan (2016), Somalia (2019) and Nigeria (2020).[25] WHO has taken some initiatives to stop the spread of *An. stephensi* in African countries.[26] *Ae. albopictus* and *Ae. aegypti* have also spread to other places, including southern Europe, North America, Oceania and Asia.[27] There are reports of expansion of malaria vectors from one region to another within India as well. *An. culicifacies* has extended its range into the northeastern states of India and is now serving as a malaria vector in those regions.[28–30] A study by Kumar *et al* found that *An. subpictus,* a non-vector species in western India, is now playing the role of malaria vector in Goa.[31] Therefore, to tackle the issue of vector incursion, regular entomological surveillance with suitable vector control tools is required. Implementation of Intergrated Vector Management (IVM) strategies that combine various control methods, such as insecticide-treated nets (ITNs), indoor residual spraying, larval source management and environmental modifications into existing public health programmes to ensure sustained vector control efforts.

Control of *Aedes* vector

In general, *Ae. aegypti* and *Ae. albopictus* are day biters in contrast to malaria vectors, which are primarily night biters. The currently available tools for the containment of *Aedes* are limited to targeting aquatic stages, that is, larvicides. Fogging for killing adult mosquitoes is carried out when a spurt in cases is seen. In a study conducted in west zone of Delhi, India, Nagpal *et al* showed that continuous entomological surveillance of *Ae. aegypti* and simultaneous appropriate interventions in key containers during non-transmission period reduced vector density and subsequently dengue cases in transmission season.[32] In another study conduted in Karnataka state, Ghosh *et al* showed effectiveness of combined information, education and communication campaigns using two potential poeciliid larvivorous fish in indoor cement tanks for *Aedes* larval control.[33] Only a few studies have been conducted in India to assess the effectiveness of the space spraying on *Aedes* mosquito control. In a study undertaken in Chennai city to determine the efficacy of peridomestic thermal fog applications of deltacide on *Ae. aegypti* adults and larvae, thermal fogging was unsuitable for the control of indoor populations of *Ae. aegypti*.[34] A recent systematic review showed that approaches targeting the aquatic stages of mosquitoes are more effective and remain functional longer compared to measures targeting adult mosquitoes only.[35] In view of the emerging threat of *Aedes* borne infections like chikungunya, dengue and zika across the globe, there is an urgent need to develop, test and deploy suitable vector tools.

Control of JE and LF and vectors

Culex spp is the vector for JE and LF transmission in India. Vector control methods adopted by the national programme are mainly for larval control utilising environmental management and biological control methods. The control of *Culex* mosquito breeding sites generally presents a challenge due to the diverse and abundant habitats in which they thrive. These include organically rich and polluted surface water collections, shallow ponds, artificial/rainwater containers, tyres, drains, septic tanks, wells and other similar habitats. Therefore, larvivorous fishes like *Gambusia affinis* and *Poecilia reticulate* should be used to control immature mosquitoes.[36] The ultra-low volume fogging technique is the only recommended technique for adult vector control of Culex, the vector of JE.[37] To help in achieving the filariasis elimination goal as well as for JE control, effective vector control of the adult population is required, which is presently non-existent in the public health programme.

Impacts of climate change

Due to the climate-sensitive nature of cold-blooded arthropod vectors like mosquitoes, sand flies, ticks and mites, vector borne diseases are influenced by changes in the climatic factors.[38] There are reports of enhanced vulnerability and emergence of new foci of malaria transmission in Himalayan areas, as demonstrated by the use of the Providing REgional Climates for Impacts Studies (PRECIS) climate model.[38] Future climatic changes might expand the geographic distribution of *Ae. aegypti* in hot desert regions and *Ae. albopictus* in the cold, upper Himalayan regions.[39] Malaria persistence and establishment of *Aedes* in northeast of India as a consequence of climate change was recently established in a study conducted in Mizoram.[40] In addition, due to the expansion of VBDs in newer areas, there may be emergence of new vectors for which existing tools might not be effective enough. It necessitates the implementation of new vector control tools to contain the VBDs.

Migration, travel and defence areas

Non-immune migrants, travellers and armed forces personnel experience exposure to malaria vectors when travelling/posted in malaria-endemic areas. Human migration has been reported to be associated with the malaria transmission in some parts of India.[41] Moreover, migration has also been reported to play a key role in kala-azar outbreaks in Africa, India and Nepal.[42] The deployment of military personnel from endemic to holoendemic regions and vice versa also leads to the of spread new malaria parasite strains and causes localised epidemics.[43] This is also further aggravated by army troops traversing through dense jungles without access to protective measures against mosquito bites. The outdoor patrolling activities of armed forces and paramilitary personnel in malaria-endemic regions also enhance their vulnerability to malaria infections.[44] Severe morbidity is also frequently recorded among the defence personnel stationed at interstate or international border regions due to the high risks of acquiring the infection in these regions.[45] There is an urgent need to devise strategies and bring in new tools to cover the mobile population such as travellers, migrants and defence personnel.

NEW VECTOR CONTROL TOOLS

Existed vector control intervention tools which are limited by the aforementioned problems are a top concern and necessitate the development of alternative effective tools. Moreover, timely approval and deployment of these new tools in the public domain are needed, so as to make them relevant under realistic timelines. In order to increase access to safe, high-quality, effective vector control products (VCPs), WHO works in close cooperation with national regulatory agencies and partner organisations to ensure that quality VCPs are available to those who need them. The WHO PQT/VCP assesses VCPs and public health pesticide active ingredients to determine that they can be used safely and effectively and are manufactured to a high-quality standard. This is carried out by assessing product dossiers and inspecting manufacturing sites. Given below are the new vector control tools, which have the potential to be used as public health interventions against VBDs:

Next-generation insecticide-treated nets

ITNs treated with a pyrethroid insecticide alone (effective for 20 washes and 3 years of use in the field) are currently referred to as LLINs.[46] The LLINs played a key role in reducing malaria by more than half a billion in Africa between 2000 and 2015.[47] To overcome the issue of the development of insecticide resistance in malaria vectors globally, WHO has approved the use of 'new types of nets' with insecticide mixtures or synergists. Pyrethroid-treated LLINs are standard, while others are considered 'new types'.[48] Notable examples include PermaNet V.3.0 with deltamethrin and piperonyl butoxide (PBO), and veeralin with alphacyphermethrin and PBO. The new-generation ITNs with PBO show enhanced efficacy in contrast to pyrethroid-only impregnated nets.[49] Another insecticide mixture used in ITNs approved by PQ VC is alpha-cypermethrin with chlorfenapyr and alpha-cypermethrin with pyriproxyfen. Pyrethroid and pyrrole chlorfenapyr-impregnated nets have shown improved killing of the resistant vectors in comparison to nets with only pyrethroids in experimental hut studies.[50] In India, synthetic pyrethroid LLINs are in use by the national programme, while PBO nets have recently recieved approval for public health use[51]. Demonstration of advantage of PBO nets over synthetic pyrethroid nets and subsequent adoption of PBO nets by NCVBDC could pave the way for their application against resistant *An. culicifacies*.

New molecules/formulations for indoor residual spraying

The emergence of resistance to DDT and synthetic pyrethroids has prompted the exploration of alternative insecticides for use in IRS. In a trial conducted for IRS using Fludora Fusion (a mixture of deltamethrin and clothianidin), enhanced and prolonged mortality of wild pyrethroid-resistant malaria vectors was observed for up to 7–10 months, primarily attributed to clothianidin component. The pyrethroid component in the mixture also led to substantial early exiting of mosquitoes from treated huts.[52] Another study in Gujarat, India, using Fludora Fusion WP-SB (clothianidin and 62.5 deltamethrin), reported equal or better efficacy compared with deltamethrin and bendiocarb alone against pyrethroid-resistant malaria vector population.[53] In Tanzania, IRS with SumiShield 50 WG (Clothianidin 50%, w/w) was found effective against insecticide-resistant *An. arabiensis* mosquito vectors. In Karnataka, India, IRS with SumiShield 50 WG demonstrated effectiveness for up to 6 months against pyrethroid-resistant *An. culicifacies*.[54] A small-scale field study in Tanzania evaluated the effectiveness of IRS against malaria-carrying mosquitoes. It reported a prolonged residual efficacy using deltamethrin 62.5 SC-PE compared with DDT 75% water-dispersible powder.[55] Deltamethrin 62.5 polymer-enhanced suspension concentrate also exhibited prolonged effectiveness, up to 5 months, compared with deltamethrin 2.5%.[56] The WHO PQVC list includes clothianidin, both as a separate moiety and in combination with deltamethrin, for IRS application. These new IRS formulations are much needed intervention tools in India, especially in the management of insecticide-resistant malaria vector species and longer residual efficacy.

New molecules/formulation for larvicides

Three major types of larval control agents, that is, (a) microbial larvicides (eg, Bacterial Larvicides; *Bacillus thuringiensis* israelensis (*Bti*) and *B. sphaericus* (*Bs*)), (b) insect growth inhibitors (pyriproxyfen, diflubenzuron) and (c) chemical insecticide (mainly temephos)) are used for vector control. The microbial larvicides, currently available are characterised by short and declining residual activity, necessitating frequent reapplication, which adds to the total cost of the control interventions. To overcome the bottlenecks of the conventionally used microbial larvicides, newer and more efficient larvicidal formulations have been developed that release effective levels of its active ingredients at the water surface with prolonged residual activities. Large-scale intervention in western Kenya showed that a single application of the formulations of *Bti* and *Bs* showed a reduction of 60%–80% of the pupal production with a prolonged activity for almost 10 weeks with no impact on non-targeted organisms.[57–59] ICMR-Vector Control Research Centre isolated indigeneous Bti 'VCRC B 17' and developed it as a bacterial biolarivicide for use in public health programme. It is also identified as Indian standard reference strain to compare the quality of other Bti products in India. Trials of long-lasting larvicide formulations of *Bti* in India should be carried out to ensure the availability of newer efficient formulations in the instance of the development of resistance against the currently used larvicides.

Attractive toxic sugar baits

Attractive toxic sugar baits (ATSB) strategy is based on the exploitation of the predilection of mosquitoes towards sugars. An important characteristic of ATSB is that it targets both female and male mosquitoes and minimises insecticide resistance due to the use of toxicants with different modes of action. It has been reported that ATSB has been effective in reducing the densities of mosquitoes (Anopheles, *Aedes* and Culex) and sand fly vectors.[60–62] In a field trial conducted in Mali, *An. gambiae* densities were reduced to 90% with a single outdoor application of boric acid-based ATSB.[61] In a laboratory trial conducted in India, *An. culicifacies, An. stephensi* and *Ae. aegypti* experienced >90% mortality with 2% boric acid-based toxic sugar bait.[63] The impact of ATSB might be exponential in conjunction with LLINs as mosquitoes deprived of blood meals take more and larger sugar meals.[64 65] Furthermore, biolarvicide *B. spharicus* has been used in ATSB to suppress larval populations of *An. sergentii* in Jordan.[66] In India, the use of ATSB strategies may be efficient under urban conditions where the availability of flowering plants is scarce limiting the feeding opportunities for mosquito populations. Apart from urban areas, regions with patchy vegetation such as Rajasthan and Gujarat can be ideal areas for ATSB strategy, due to the limited availability of natural sugar sources in these patchy vegetation. For rural vectors, the strategy employed by N'do *et al* in which can be of great use in which *Bti* sugar patches were attached to bed nets, which resulted in the killing of insecticide-resistant mosquitoes landing on the bed nets.[67] The Indian Council of Medical Research has developed a standardised methodology for testing ATSB in both laboratory and field settings (www.icmr.nic.in). This methodology will prove beneficial for researchers and the insecticide industry to test the ATSB in a robust scientific way.

Ivermectin-like endectocides

Endectocides are drugs that have both ecto and endo parasiticidal activity. Ivermectin is the most commonly recommended endectocide for vector control purposes. The application of ivermectin has multiple advantages including efficacy against both endophagic and exophagic vectors, minimal chance of insecticide resistance due to different modes of action, kills mosquitoes as well as the malaria parasite. In Africa's endemic regions, ivermectin trials have been carried out and have been reported with encouraging outcomes.[68] According to Mekuriaw *et al*'s study, mosquitoes that fed on blood treated with ivermectin displayed a higher mortality rate compared with the control group.[69] Further research has shown that administering standard veterinary doses of ivermectin to cattle results in a significant decrease in the survival rates of *An. epiroticus* and *An. dirus*.[70] In India, ivermectin as sugar bait was found effective against resistant *An. culicifacies* and *An. stephensi*.[71] Ivermectin is already in use in the LF control programme of India. Before its use in the vector control programme, trials of ivermectin should be conducted against different vectors followed by preclinical and clinical trials in humans as well as cattle.[68] Drug administration of ivermectin in malaria-persistent areas either to cattle or humans might help control the disease transmission.

Insecticidal paints

Insecticidal paint is one of the innovative vector control strategies that involves microencapsulated insecticides embedded within the paint matrix. Unlike IRS, insecticidal paints do not require skilled/trained personnel or logistical planning. Application of insecticidal paints resulted in ≥90% mortality of *An. gambiae* mosquitoes both under laboratory and field conditions.[72 73] Acharya *et al* also reported insecticidal activity for an insecticidal paint formulation against *Ae. aegypti* in a study conducted in India, where a 94% knockdown and 90% mortality with a residual efficacy of almost 18 months was observed.[74] In another laboratory trial involving insecticide paint formulations, significant behavioural avoidance was observed in vectors of dengue, malaria and filariasis.[75] India may consider further development and evaluation of the insecticidal paints due to their ease of application, efficacy against insecticide-resistant vectors and targeted approach before possible adoption by the national programme.

Tools for animal shelters

An. culicifacies, An. stephensi and *An. fluviatilis* mosquitoes are responsible for transmitting the majority of malaria cases in India, which rest in cattle sheds and feed on both cattle and humans. The densities of these mosquitoes can be reduced either by spraying cattle shelters or by applying insecticide topically on cattle.[76] A community-level randomised controlled trial reported from Pakistan study on highly zoophilic mosquitoes showed a drastic reduction in the malaria incidence with the topical application of insecticides.[77] Another study reported from India showed that the IRS in houses and cattle sheds yielded a higher reduction in malaria cases in comparison to individual treatments.[78] The use of deltamethrin-treated ITNs in covering the pigsties was found to be effective in deterring mosquitoes away from the pigs, which act as the amplifying host of the JE virus, thereby curtailing the bridge of contact with the reservoir.[79] As the topical application of insecticide to each cattle can be impractical, IRS or application of insecticidal paint on walls of cattle sheds might be used in controlling the vector populations.

Insecticide-treated wearables and materials

Insecticide-treated materials/wearables include clothing, bed nets or other personal items treated with insecticides. When individuals use or wear these treated materials outdoors, they create a protective barrier that repels or kills mosquitoes on contact. This is particularly effective in preventing outdoor mosquito bites, reducing the risk of VBDs like malaria. Insecticide-treated clothing and fabrics have been employed as personal protective wearables, particularly in military and recreational settings, as a means of safeguarding against insect bites.[80 81] The insecticide-treated clothing can be an easy-to-use tool for protecting against vectors and can easily be integrated into everyday routines at work or educational spaces such as industrial/defence/school.[81] Insecticide-treated materials or wearables and spatial repellents serve as valuable tools in addressing outdoor mosquito biting. Permethrin, a synthetic pyrethroid, is a prevalent ingredient employed in fabrics, while alternative compounds, such as deltamethrin, cyfluthrin, bifenthrin, KBR3023 and DEET (N, N-diethyl-3-methylbenz-amide), have also been tested.[80] A modelling study by Massad *et al* reported that impregnating school uniforms with insecticide can lower dengue incidence in school children by at least 6%–55%.[82] Another report by Banks *et al* highlighted that insecticide-impregnated clothing could provide around 0%–75% and 0%–79% protection against malaria and leishmaniasis, respectively.[80] In a field trial of deltamethrin-treated curtains, a significant reduction (87.9%–93.7%) of *An. stephensi* and *Ae. aegypti* was reported in India.[83] Therefore, these insecticide-treated clothing or hammocks can be a good option for protection from indoor and outdoor biting mosquitoes. Moreover, these might be useful for migratory populations and armed force personnel who are at risk of vector bites.

Spatial Repellents (SRs)

Spacial reppellents offer protection against blood-seeking vectors, such as mosquitoes, by releasing airborne chemicals.[1] SRs deter mosquitoes from entering a defined space, such as a room or outdoor area. This technology is beneficial for outdoor settings where conventional methods like bed nets may be impractical. SRs provide a localised solution to protect individuals in specific areas from mosquito bites. Various chemicals have been reported to show insect-repelling properties. Metofluthrin and transfluthrin, which are volatile pyrethroids, as well as terpenoids derived from plants, and volatile organic compounds present on human skin, and organic compounds released by skin bacteria, such as 1-methyl piperazine, exhibit properties of spatial insect repellents. SRs might be useful in protection from vector bites when (1) vector biting is outdoors, (2) when LLINs are irregularly used or not used at all, (3) when vectors are restricted from resting or have limited resting time on indoor surfaces treated with insecticide and (4) when IRS or LLINs are neither accessible nor practical, SRs may be an added advantage in reducing VBDs.[84 85] Several trials have been conducted to demonstrate the efficacy of SR products against malaria and other disease vectors.[86–89] In a randomised household trial carried out in China evaluating mosquito coils, it was observed that coils alone could provide 77% protective efficacy against *P. falciparum* using 0.03% transfluthrin coils.[86] A field study in Indonesia using metofluthrin as a SR in mosquito coils resulted in a 52% increase in malaria protection.[88] Therefore, the application of SRs can help minimise vector bites, resulting in the containment of the VBDs. SRs will be useful to migratory people and armed force personnel in India due to their regular movements outdoors making them receptive to vector bites.

CONCLUSION

We have discussed the prospects, feasibility and availability of the new vector control tools in the Indian scenario to provide a ready-to-use guide to the national programme. The control of VBDs is of utmost importance for any public health programme. India has planned for elimination of three of the VBDs malaria, kala-azar and lymphatic filariaisis. The currently available tools for vector control in India rely heavily on IRS and LLIN using a limited number of chemical insecticides. The development of insecticide resistance among major vectors, changes in vector behaviour, outdoor biting patterns and the impact of climate change have made it increasingly difficult to control and eliminate VBDs using conventional methods. Therefore, there is an urgent need for new vector control tools that can be employed by the national VBD control programme of India.

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ORCID iDs
Gaurav Kumar http://orcid.org/0000-0002-8407-9056
Amit Sharma http://orcid.org/0000-0002-3305-0034
Manju Rahi http://orcid.org/0000-0003-0932-0935

REFERENCES

1 World Health Organization (WHO). Global vector control response 2017-2030. World Health Organization; 2017. Available: https://apps.who.int/iris/handle/10665/259205 [Accessed 23 Mar 2023].
2 Campbell-Lendrum D, Manga L, Bagayoko M, *et al*. Climate change and vector-borne diseases: what are the implications for public health research and policy? *Philos Trans R Soc Lond B Biol Sci* 2015;370.
3 World Health Organization. World malaria report 2022. World Health Organization; 2022. Available: https://www.who.int/publications/i/item/9789240064898 [Accessed 23 May 2023].
4 NCVBDC (National Center for Vector Borne Diseases Control). Diseases. 2021. Available: https://ncvbdc.mohfw.gov.in/index4.php?lang=1&level=0&linkid=407&lid=3683 [Accessed 10 Mar 2023].
5 Rahi M, Chaturvedi R, Das P, *et al*. India can consider integration of three eliminable disease control programmes on malaria, lymphatic filariasis, and visceral leishmaniasis. *PLoS Pathog* 2021;17:e1009492.
6 Yadav CP, Sharma A. National Institute of malaria research-malaria dashboard (NIMR-MDB): a digital platform for analysis and visualization of epidemiological data. *Lancet Reg Health Southeast Asia* 2022;5:100030.
7 Singh RK, Kumar G, Mittal PK. Insecticide susceptibility status of malaria vectors in India: a review. Int J Mosq Res 2014;1:5–9.
8 Raghavendra K, Velamuri PS, Verma V, *et al*. Temporo-spatial distribution of insecticide-resistance in Indian malaria vectors in

the last quarter-century: need for regular resistance monitoring and management. *J Vector Borne Dis* 2017;54:111–30.
9 Raghavendra K, Rahi M, Verma V, *et al*. Insecticide resistance status of malaria vectors in the malaria endemic states of India: implications and way forward for malaria elimination. *Heliyon* 2022;8:e11902.
10 Singh RK, Haq S, Kumar G, *et al*. Insecticide susceptibility status of dengue vectors aedes aegypti and aedes albopictus in India: a review. *Dengue Bulletin* 2013;37:177–91.
11 Kushwah RBS, Mallick PK, Ravikumar H, *et al*. Status of DDT and pyrethroid resistance in indian aedes albopictus and absence of knockdown resistance (KDR) mutation. *J Vector Borne Dis* 2015;52:95–8.
12 Dhiman RC, Yadav RS. Insecticide resistance in phlebotomine sandflies in Southeast Asia with emphasis on the Indian subcontinent. *Infect Dis Poverty* 2016;5:106.
13 Dinesh DS, Hassan F, Kumar V, *et al*. Insecticide susceptibility of phlebotomus argentipes sandflies, vectors of visceral leishmaniasis in India. *Trop Med Int Health* 2021;26:823–8.
14 Mandal R, Kumar V, Kesari S, *et al*. Assessing the combined effects of household type and insecticide effectiveness for Kala-Azar vector control using indoor residual spraying: a case study from North Bihar, India. *Parasit Vectors* 2019;12:409.
15 Dev V, Adak T, Singh O, *et al*. Malaria transmission in Tripura: disease distribution & determinants. *Indian J Med Res* 2015;142:12.
16 Kumari R, Kumar K, Rawat A, *et al*. First indigenous transmission of Japanese encephalitis in urban areas of national capital territory of Delhi, India. *Tropical Med Int Health* 2013;18:743–9.
17 Mariappan T, Samuel PP, Thenmozhi V, *et al*. Entomological investigations into an epidemic of Japanese encephalitis (JE) in northern districts of West Bengal, India (2011-2012). *Indian J Med Res* 2014;139:754–61.
18 Sougoufara S, Ottih EC, Tripet F. The need for new vector control approaches targeting outdoor biting anopheline malaria vector communities. *Parasit Vectors* 2020;13:295.
19 Rath A, Prusty MR, Das M, *et al*. A shift in resting habitat and feeding behavior of anopheles fluviatilis sibling species in the Keonjhar District of Odisha, India. *Trans R Soc Trop Med Hyg* 2015;109:730–7.
20 Rahi M, Mishra AK, Chand G, *et al*. Countrywide surveillance of malaria vector bionomics and its implications for malaria elimination in India. *JMIR Preprints* 2022.
21 Gupta SK, Saroha P, Singh K, *et al*. Malaria epidemiology along the Indian districts bordering Bhutan and implications for malaria elimination in the region. *Am J Trop Med Hyg* 2021;106:655–60.
22 Sarmah NP, Bhowmik IP, Sarma DK, *et al*. Role of anopheles baimaii: potential vector of epidemic outbreak in Tripura, North-East India. *J Glob Health Rep* 2019;3:e2019036.
23 Galagan SR, Prue CS, Khyang J, *et al*. The practice of Jhum cultivation and its relationship to Plasmodium Falciparum infection in the Chittagong hill districts of Bangladesh. *Am J Trop Med Hyg* 2014;91:374–83.
24 WHO. Vector alert: Anopheles Stephensi invasion and spread. 2019. Available: https://www.who.int/news/item/26-08-2019-vector-alert-anopheles-stephensi-invasion-and-spread [Accessed 23 May 2023].
25 Sinka ME, Pironon S, Massey NC, *et al*. A new malaria vector in Africa: predicting the expansion range of anopheles stephensi and identifying the urban populations at risk. *Proc Natl Acad Sci U S A* 2020;117:24900–8.
26 WHO. WHO initiative to stop the spread of Anopheles Stephensi in Africa WHO/UCN/GMP/2022.06. 2023. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7552528/ [Accessed 23 May 2023].
27 Näslund J, Ahlm C, Islam K, *et al*. Emerging mosquito-borne viruses linked to aedes aegypti and aedes albopictus: global status and preventive strategies. *Vector-Borne and Zoonotic Diseases* 2021;21:731–46.
28 Saxena R, Nagpal BN, Singh VP, *et al*. Impact of deforestation on known malaria vectors in Sonitpur District of Assam, India. *J Vector Borne Dis* 2014;51:211–5.
29 Akhtar N, Nagpal BN, Kapoor N, *et al*. Role of an. *Culicifacies* as a vector of malaria in changing ecological scenario of northeastern States of India. *J Vector Borne Dis* 2016;53:264–71.
30 Dhiman RC, Yadav Y, Singh P. Ecological change resulting in high density of anopheles culicifacies in Karbi Anglong district, Assam, India. *J Vector Borne Dis* 2020;57:371–4.
31 Kumar A, Hosmani R, Jadhav S, *et al*. Anopheles subpictus carry human malaria parasites in an urban area of Western India and may facilitate perennial malaria transmission. *Malar J* 2016;15:124.
32 Nagpal BN, Gupta SK, Shamim A, *et al*. Control of aedes aegypti breeding: a novel intervention for prevention and control of dengue in an endemic zone of Delhi, India. *PLoS ONE* 2016;11:e0166768.
33 Ghosh SK, Chakaravarthy P, Panch SR, *et al*. Comparative efficacy of two poeciliid fish in indoor cement tanks against chikungunya vector aedes aegypti in villages in Karnataka, India. *BMC Public Health* 2011;11:599.
34 Mani TR, Arunachalam N, Rajendran R, *et al*. Efficacy of thermal fog application of deltacide, a synergized mixture of pyrethroids, against aedes aegypti, the vector of dengue. *Trop Med Int Health* 2005;10:1298–304.
35 Montenegro-Quiñonez CA, Louis VR, Horstick O, *et al*. Interventions against aedes/dengue at the household level: a systematic review and meta-analysis. *EBioMedicine* 2023;93:104660.
36 Chandra G, Bhattacharjee I, Chatterjee SN, *et al*. Mosquito control by larvivorous fish. *Indian J Med Res* 2008;127:13–27.
37 Ministry of Health & Family Welfare (MOHFW), Government of India. Operational guidelines national programme for prevention and control of Japanese Encephalitis/ acute encephalitis syndrome. 2014. Available: https://nvbdcp.gov.in/Doc/JE-AES-Prevention-Control(NPPCJA).pdf [Accessed 23 May 2023].
38 Dhiman RC, Pahwa S, Dhillon GPS, *et al*. Climate change and threat of vector-borne diseases in India: are we prepared? *Parasitol Res* 2010;106:763–73.
39 Hussain SSA, Dhiman RC. Distribution expansion of dengue vectors and climate change in India. *GeoHealth* 2022;6.
40 Karuppusamy B, Sarma DK, Lalmalsawma P, *et al*. Effect of climate change and deforestation on vector borne diseases in the North-Eastern Indian state of Mizoram bordering Myanmar. JCCH 2021;2:100015.
41 Kumar A. Some considerable issues concerning malaria elimination in India. *J Vector Borne Dis* 2019;56:25.
42 Kumar A, Saurabh S, Jamil S, *et al*. Intensely clustered outbreak of visceral leishmaniasis (Kala-Azar) in a setting of seasonal migration in a village of Bihar, India. *BMC Infect Dis* 2020;20:10.
43 Aggarwal S, Gupta P, Mahajan N, *et al*. Implementation of drone based delivery of medical supplies in North-East India: experiences, challenges and adopted strategies. *Front Public Health* 2023;11:1128886.
44 Dhiman S, Gopalakrishnan R, Goswami D, *et al*. Malaria incidence among paramilitary personnel in an endemic area of Tripura. *Indian J Med Res* 2011;133:665–9.
45 Patra SS, Dev V. Malaria related morbidity in central reserve police force personnel located in the North-Eastern States of India. *Journal of Human Ecology* 2004;15:255–9.
46 Ng'ang'a PN, Aduogo P, Mutero CM. Long lasting Insecticidal mosquito nets (Llins) ownership, use and coverage following mass distribution campaign in Lake Victoria Basin, Western Kenya. *BMC Public Health* 2021;21:1046.
47 Bhatt S, Weiss DJ, Cameron E, *et al*. The effect of malaria control on plasmodium falciparum in Africa between 2000 and 2015. *Nature* 2015;526:207–11.
48 Ngufor C, Agbevo A, Fagbohoun J, *et al*. Efficacy of royal guard, a new alpha-cypermethrin and pyriproxyfen treated mosquito net, against pyrethroid-resistant malaria vectors. *Sci Rep* 2020;10:12227.
49 Mosha JF, Kulkarni MA, Lukole E, *et al*. Effectiveness and cost-effectiveness against malaria of three types of dual-active-ingredient long-lasting insecticidal nets (Llins) compared with pyrethroid-only llins in tanzania: a four-arm, cluster-randomised trial. *Lancet* 2022;399:1227–41.
50 Bayili K, N'do S, Namountougou M, *et al*. Evaluation of efficacy of interceptor G2, a long-lasting insecticide net coated 196 with a mixture of chlorfenapyr and alpha-cypermethrin, against pyrethroid resistant anopheles gambiae sl in Burkina Faso. *Malar J* 2017;16:190.
51 Kasinathan G, Sahu SS, Krishnamoorthy N, *et al*. Efficacy evaluation of Veeralin LN, a PBO-incorporated alpha-cypermethrin long-lasting insecticidal net against anopheles culicifacies in experimental huts in Odisha state. *Malar J* 2020;19:402.
52 Fongnikin A, Houeto N, Agbevo A, *et al*. Efficacy of fludora® fusion (a mixture of deltamethrin and clothianidin) for indoor residual spraying against pyrethroid-resistant malaria vectors: laboratory and experimental hut evaluation. *Parasit Vectors* 2020;13:466.
53 Kamaraju R, Pant CS, Uragayala S, *et al*. Small-scale field evaluation of the entomological efficacy and the residual activity of fludora® fusion WP-SB indoor residual spraying against anopheles culicifacies S.L. *Trop Med Int Health* 2021;26:469–77.
54 Sreehari U, Raghavendra K, Tiwari SN, *et al*. Small-scale (phase II) evaluation of the efficacy and residual activity of sumishield® 50 WG (clothianidin 50%, W/W) for indoor residual spraying in comparison to deltamethrin, bendiocarb and pirimiphos-methyl for malaria vector control in Karnataka state, India. *J Vector Borne Dis* 2018;55:122–9.
55 World Health Organization (WHO). Report of the sixteenth WHOPES working group meeting: WHO/HQ. World Health Organization; 2013.

56 Sahu SS, Thankachy S, Dash S, *et al*. Evaluation of long-lasting indoor residual spraying of deltamethrin 62.5 SC-PE against malaria vectors in India. *Malar J* 2020;19:19.
57 Derua YA, Kahindi SC, Mosha FW, *et al*. Microbial larvicides for mosquito control: impact of long lasting formulations of bacillus thuringiensis VAR Israelensis and bacillus sphaericus on non-target organisms in Western Kenya Highlands. *Ecol Evol* 2018;8:7563–73.
58 Zhou G, Lo E, Githeko AK, *et al*. Long-lasting microbial larvicides for controlling insecticide resistant and outdoor transmitting vectors: a cost-effective supplement for malaria interventions. *Infect Dis Poverty* 2020;9:162.
59 Kahindi SC, Muriu S, Derua YA, *et al*. Efficacy and persistence of long lasting microbial larvicides against malaria vectors in Western Kenya Highlands. *Parasit Vectors* 2018;11:438.
60 Qualls WA, Müller GC, Khallaayoune K, *et al*. Control of sand flies with attractive toxic sugar baits (ATSB) and potential impact on non-target organisms in Morocco. *Parasit Vectors* 2015;8:87.
61 Müller GC, Beier JC, Traore SF, *et al*. Successful field trial of attractive toxic sugar bait (ATSB) plant-spraying methods against malaria vectors in the anopheles gambiae complex in Mali, West Africa. *Malar J* 2010;9:210.
62 Kumar G, Ojha VP, Pasi S. Applicability of attractive toxic sugar baits as a mosquito vector control tool in the context of India: a review. *Pest Manag Sci* 2021;77:2626–34.
63 Kumar G, Sharma A, Dhiman RC. Laboratory evaluation of the efficacy of boric acid containing toxic sugar baits against anopheles culicifacies. *J Vector Borne Dis* 2022;59:52.
64 Stone CM, Jackson BT, Foster WA. Effects of bed net use, female size, and plant abundance on the first meal choice (blood vs sugar) of the malaria mosquito anopheles gambiae. *Malar J* 2012;11:1–2.
65 Lobo NF, Achee NL, Greico J, *et al*. Modern vector control. *Cold Spring Harb Perspect Med* 2018;8:a025643.
66 Schlein Y, Müller GC. Decrease of larval and subsequent adult anopheles sergentii populations following feeding of adult mosquitoes from bacillus sphaericus-containing attractive sugar baits. *Parasit Vectors* 2015;8:244.
67 N'do S, Bayili K, Bayili B, *et al*. Effect of bacillus thuringiensis VAR. Israelensis sugar patches on insecticide resistant anopheles gambiae s. *J Med Entomol* 2019;56:1312–7.
68 Ahmad SS, Rahi M, Saroha P, *et al*. Ivermectin as an endectocide may boost control of malaria vectors in India and contribute to elimination. *Parasit Vectors* 2022;15:20.
69 Mekuriaw W, Balkew M, Messenger LA, *et al*. The effect of Ivermectin® on fertility, fecundity and mortality of anopheles arabiensis fed on treated men in Ethiopia. *Malar J* 2019;18:357.
70 Cramer EY, Quang NX, Hertz JC, *et al*. Ivermectin treatment for cattle reduced the survival of two malaria vectors, anopheles dirus and anopheles epiroticus, under laboratory conditions in central Vietnam. *Am J Trop Med Hyg* 2021;104:2165–8.
71 Kumar G, Pasi S, Yadav CP, *et al*. Potential of Ivermectin as an active ingredient of the attractive toxic sugar baits against the Indian malaria vectors anopheles culicifacies and anopheles stephensi. *Pest Manag Sci* 2023;79:474–80.
72 Mosqueira B, Chabi J, Chandre F, *et al*. Efficacy of an insecticide paint against malaria vectors and nuisance in West Africa - part 2: field evaluation. *Malar J* 2010;9:341.
73 Mosqueira B, Duchon S, Chandre F, *et al*. Efficacy of an insecticide paint against insecticide-susceptible and resistant mosquitoes - part 1: laboratory evaluation. *Malar J* 2010;9:340.
74 Acharya BN, Ahirwar R, Dhiman S, *et al*. Deltamethrin microencapsulation in emulsion paint binder and its long-term efficacy against dengue vector aedes aegypti *Front Public Health* 2021;9:686122.
75 Dhiman S, Yadav K, Acharya BN, *et al*. Behavioural response of mosquito vectors aedes aegypti, anopheles stephensi and culex quinquefasciatus to synthetic pyrethroid and organophosphorus-based slow-release Insecticidal paint. *Parasit Vectors* 2021;14:259.
76 Waite JL, Swain S, Lynch PA, *et al*. Increasing the potential for malaria elimination by targeting zoophilic vectors. *Sci Rep* 2017;7:40551.
77 Rowland M, Durrani N, Kenward M, *et al*. Control of malaria in Pakistan by applying deltamethrin insecticide to cattle: a community-randomised trial. *The Lancet* 2001;357:1837–41.
78 Ansari MA, Sharma VP, Razdan RK, *et al*. The value of spraying cattle sheds in a control programme. *Indian J Malariol* 1988;25:17–22.
79 Dutta P, Khan SA, Khan AM, *et al*. The effect of insecticide-treated mosquito nets (Itmns) on Japanese encephalitis virus seroconversion in pigs and humans. *Am J Trop Med Hyg* 2011;84:466–72.
80 Banks SD, Murray N, Wilder-Smith A, *et al*. Insecticide-treated clothes for the control of vector-borne diseases: a review on effectiveness and safety. *Med Vet Entomol* 2014;28:14–25.
81 DeRaedt Banks S, Orsborne J, Gezan SA, *et al*. Permethrin-treated clothing as protection against the dengue vector, aedes aegypti: extent and duration of protection. *PLoS Negl Trop Dis* 2015;9:e0004109.
82 Massad E, Amaku M, Coutinho FAB, *et al*. Theoretical impact of insecticide-impregnated school uniforms on dengue incidence in Thai children. *Glob Health Action* 2013;6:20473.
83 Ansari MA, Razdan RK. Concurrent control of mosquitoes and domestic pests by use of deltamethrin-treated curtains in the new delhi municipal committee, India. *J Am Mosq Control Assoc* 2001;17:131–6.
84 Durnez L, Coosemans M. *Residual Transmission of Malaria: An Old Issue for New Approaches. Anonymous Anopheles Mosquitoes - New Insights into Malaria Vectors*. London, United Kingdom: IntechOpen, 2013.
85 Harvey SA, Lam Y, Martin NA, *et al*. Multiple entries and exits and other complex human patterns of insecticide-treated net use: a possible contributor to residual malaria transmission? *Malar J* 2017;16:265.
86 Hill N, Zhou HN, Wang P, *et al*. A household randomized, controlled trial of the efficacy of 0.03% transfluthrin coils alone and in combination with long-lasting insecticidal nets on the incidence of plasmodium falciparum and plasmodium vivax malaria in Western Yunnan province, China. *Malar J* 2014;13:208.
87 Ritchie SA, Devine GJ. Confusion, knock-down and kill of aedes aegypti using metofluthrin in domestic settings: a powerful tool to prevent dengue transmission *Parasit Vectors* 2013;6:262.
88 Syafruddin D, Bangs MJ, Sidik D, *et al*. Impact of a spatial repellent on malaria incidence in two villages in Sumba, Indonesia. *Am J Trop Med Hyg* 2014;91:1079–87.
89 Syafruddin D, Asih PB, Rozi IE, *et al*. Efficacy of a spatial repellent for control of malaria in indonesia: a cluster-randomized controlled trial. *Public and Global Health* [Preprint] 2019.