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Vector Control Strategies and Challenges: A Narrative Review

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ABSTRACT

Vector-borne diseases remain a major global public health challenge, disproportionately affecting low- and middle-income countries. Traditional control measures such as insecticide-treated bed nets, indoor residual spraying, and environmental management have reduced disease burden but face limitations due to insecticide resistance, inadequate infrastructure, and changing ecological conditions. This review synthesizes evidence on conventional and emerging strategies for vector control, including genetic approaches, biological interventions, and community-led initiatives. Case studies from Africa, Asia, and Latin America demonstrate that integrated vector management (IVM) tailored to local contexts offers the most sustainable path forward. Novel technologies such as CRISPR-based gene drives, Wolbachia-based biocontrol, and smart surveillance tools present promising innovations, though their ethical and ecological implications require careful consideration. The review emphasizes the need for multi-sectoral collaboration, community engagement, and policy support to ensure long-term effectiveness. Addressing these challenges holistically will be crucial to curbing the global burden of vector-borne diseases and preventing future outbreaks.

Keywords: Vector-borne diseases, integrated vector management (IVM), Insecticide resistance, Genetic and biological control, and Community participation.

INTRODUCTION

Vector-borne diseases pose a significant threat to global physical security by endangering food safety and raw material supply chains [1]. They underpin extensive well-being and monetary expenses, highlighting the difficulty of controlling vector populations once established in a locale. A particular vector of focus, the Aedes aegypti mosquito, is widely associated with transmitting diseases such as the Zika virus, Dengue fever, Chikungunya, and Yellow fever. Vector control efforts are hindered by difficulties in locating breeding zones, food sources, and the increasing resistance of various species to conventional methods. Existing control strategies are measured with linear feedback control methods, and ongoing research aims to develop alternative approaches to improve feasibility and adaptability [2]. These set the framework for a narrative review on vector control strategies and challenges. Vector-borne diseases present a pervasive threat to global health and security. The Aedes aegypti mosquito is a vector for several virulent diseases. Control efforts face challenges in locating breeding zones and food sources, alongside resistance to conventional methods. Existing strategies are measured with linear feedback control, and alternative approaches are under investigation to enhance feasibility and adaptability [1, 2].

Background on Vector-Borne Diseases

Vector-borne diseases (VBDs) account for more than 17% of all infectious diseases, with over one billion cases and more than one million deaths annually[1, 12]. The global burden of VBDs remains high because of difficulties with prevention and control, and most transmitted pathogens lack vaccines. Distribution is governed by a combination of environmental and social determinants [1, 23]. Increased globalization, rapid urbanization and migration, and climate change further contribute to transmission. Among these diseases, dengue, chikungunya, and Zika chiefly constitute urban concerns. Widely distributed and extremely common invasive vectors such as Aedes aegypti and Aedes albopictus augment transmission [24, 25]. Urban environments, especially in developing countries, provide optimal conditions for the proliferation of these diseases, threatening populations. By contrast, countries with a high standard of living are primarily concerned with prevention of introduction or re-emergence, as illustrated by several recent outbreaks of Zika virus in the Americas and the persistent resurgence of endemic malaria in parts of Southern Europe [3, 14]. In both contexts, early detection of the vectors and their potential pathogens is essential to identify the risks related to the spread of VBDs, implement control measures, and monitor the impact of already established vector populations [6, 23]. The foundation of a response strategy lies in surveillance systems capable of collecting and analysing data and providing support for relevant and timely public health policies related to environmental conditions and human activities. A scoping review was undertaken to map existing literature and identify methods and research gaps, focusing on VBD surveillance (vectors and pathogens) in the urban environment and its translation into health actions, investigating how surveillance systems are set up, which components are included, and how collected data are used to effectively adapt health policies. Challenges related to unique urban factors were also explored at the end of the process [3]. Vector-borne diseases, a collection of illnesses caused by parasites, viruses, and bacteria transmitted by blood-feeding arthropods, account for more than 17% of all infectious diseases and remain major public-health problems in the 21st century [4]. Large-scale and coordinated control programmes have contributed to a substantial decline in global mortality linked to VBDs. However, environmental alterations, including climate change, are expected to have a significant impact on VBD-related hazards, vulnerabilities, and exposures [2, 4]. The African continent is particularly vulnerable to VBDs under climate change, but research efforts are insufficient to adequately inform effective and long-term public-health policies [4].

Overview of Vector Control Strategies

Vector-borne diseases are transmitted by arthropod vectors such as mosquitoes, ticks, sand flies, and triatomine bugs [4, 25]. The transmission of these pathogens relies on the abundance and population dynamics of vectors, which are strongly affected by biological, ecological, environmental, and socioeconomic determinants. Vector control is one of the most important strategies to reduce the burden of vector-borne diseases [8, 9]. The development of effective and sustainable vector control strategies remains a challenge, since their implementation needs to consider a wide range of factors, including insecticide resistance, the ecological impact of interventions, financial restrictions, and cultural practices [2, 7]. Various vector control strategies have been implemented over the years. In general, they can be classified as chemical, biological, environmental, or genetic vector control methods [1, 5].

Chemical Control Methods

Vector control plays a vital role in disease prevention, control, and elimination [5, 24]. The Global Vector Control Response 2017–2030 was launched by the World Health Organization (WHO) as a strategy to enhance implementation of locally adapted and sustainable vector control [7, 24]. The use of insecticides remains the mainstay of vector control worldwide, typically applied as treated nets, residual spraying, larviciding, and space spraying. Residual spraying includes indoor residual spraying (IRS) and outdoor insecticide application in larval habitats. Larviciding involves applying insecticides to aquatic habitats to kill immature mosquito stages. Space spraying uses fog to create a short-term effect on flying mosquitoes, mainly applied during dengue outbreaks [5, 17]. Ten of the 32 articles selected for this review investigated chemical vector control [2, 18]. The number of publications addressing chemical methods remains approximately constant over the years, reflecting its ongoing dominant role in contemporary vector control [7, 23]. The heavy reliance on insecticides has become increasingly controversial, largely because of the risk of adverse health and environmental effects, together with the global emergence of widespread insecticide resistance in vectors, which threatens the effectiveness of vector control interventions [3, 22].

Biological Control Methods

Control strategies employing biological means rely on natural enemies of mosquitoes, including predators and parasites, to regulate vector populations [1, 13]. Indoor residual spraying tends to be more effective against endophilic species such as Aedes aegypti than outdoor vectors like Aedes albopictus [1]. Integrated vector management promotes a science-based framework emphasizing population monitoring, problem identification, and development of novel techniques [9, 10]. Ensuring the carrying capacity of vectors remains below epidemiologically significant levels during interepidemic periods is essential for sustained control. Despite the longstanding use of introduced predators in mosquito control, there is limited evidence demonstrating measurable reductions in either vector abundance or disease incidence [6]. Experimental biological interventions also encompass larval control agents such as larvivorous fish, cyclopoid copepods, and Bacillus thuringiensis israelensis (Bti) formulations. Larvivorous fish may not be suitable for extensive deployment despite efficacy in confined settings, whereas copepods have shown promise in reducing dengue transmission, albeit results vary with concurrent control activities 7. Bti effectively kills larvae and suppresses adult emergence; however, the impact is transient and should be integrated with complementary measures [1, 6]. Additional avenues under investigation include the sterile insect technique (SIT), genetically modified mosquitoes, and Wolbachia-based approaches. Conventional SIT entails mass release of radiation-sterilized males to diminish reproductive capacity, but challenges persist in male-only separation and potential fitness detriments [5, 23]. Release of insects carrying dominant lethality traits, such as flightless females, seeks to overcome some of these constraints [7, 9].

Environmental Management

The control of disease vectors encompasses a variety of approaches categorized as chemical, biological, environmental, and genetic. Environmental strategies aim to prevent vector reproduction and reduce contact between vectors, human populations, and domestic animals [1, 3]. The Aedes aegypti mosquito, vector of several arboviral diseases, preferentially breeds indoors in water-filled containers ranging from large tanks to small receptacles; containers in backyards are also suitable habitats. Environmental control methods target the elimination or modification of vector habitats to reduce vector populations and interaction with humans, involving several specific actions [1]. Habitat Modification: Long-term alterations to the environment impede vector breeding, such as draining swamps, filling or leveling land, or improving irrigation to prevent unintended water bodies [1, 6]. These measures require community involvement and government support due to their scope and resource demands. Continuous surveillance is essential to detect the reappearance of vectors [8, 2]. Habitat Manipulation: Temporary changes in the environment, distinguished from habitat modification by their reversibility, seek to reduce vector breeding sites on a short-term basis. Activities include generalized water management to eliminate stagnant water, intermittent irrigation practices, scheduled draining and wetting of rice fields, and removal or covering of water storage containers to restrict breeding opportunities [9, 3]. Sanitation Source Reduction: Linked closely with habitat modification, sanitation efforts focus on the disposal or recycling of items that collect water or maintenance of drains and water storage facilities [7, 10]. Source reduction campaigns engage community participation to eliminate or manage potential breeding sites, often forming the initial step in routine vector control programs [4, 6]. Environmental management strategies are essential components of integrated vector management but require continuous implementation to maintain effectiveness [7, 23]. Their success depends on adequate infrastructure, public cooperation, and governmental policies supporting environmental modifications and sanitation [8, 13].

Genetic Control Techniques

These techniques allow specific genetic changes in vector populations [10]. Approaches focus on population reduction, population replacement, or driving desired genetic alterations through wild populations [11]. The sterile insect technique (SIT) and similar methods release excessive numbers of sterile males to reduce reproduction, requiring frequent additive releases. Gene-drive methods, transgenic or nontransgenic, can spread genetic modifications throughout wild populations, overcoming the constraints of repeated releases [10, 11].

Challenges in Vector Control

Insecticide resistance among disease vectors is a persistent weakness, including vectors of malaria, dengue, leishmaniasis, and schistosomiasis [9]. Widespread and intensifying resistance arises mainly from shortcomings in pesticide lifecycle management [10]. The high reliance of vector-borne disease control programmes on a limited number of insecticides (mostly pyrethroids) and application methods (indoor residual spray, insecticide-treated nets, fogging, and space spray) gives resistance management a particularly central role [1, 2]. Although service providers often retain the knowledge and capacity to include resistance management in practice, policymakers do not always prioritise the challenge [11, 24]. The economies of scale and scope present in vector control further exacerbate these effects on insecticide resistance because even if a single programme implements insecticides responsibly, alternatives in the same country or region might not[6, 8]. Other potential entry points of insecticides into the environment, such as agriculture and household products, can also influence and undermine vector control efforts of resistance management [3, 16].

Insecticide Resistance

Control of vectors with chemicals generally consists of spatial treatments of water or breeding sites with larvicides, and indoor or outdoor treatments with residual or space spray insecticides [1, 2]. While the development of insecticide resistance in target vectors is well documented [12], at a global scale, insecticide use for vector control is relatively unchanged. Insecticide use under the global malaria programme peaked in 2010 and totalled nearly 2 million tonnes of active ingredient annually [5]. Insecticide resistance was still confined to localized areas, but selective redistribution of insecticides to where resistance was not yet present allowed the programme to operate on a larger scale with limited impacts on overall insecticide use [5, 12]. The cycle of increased insecticide use leading to development of resistance and increased insecticide use, also observed in the agricultural sector, suggests that trends in insecticide use alone are misleading as an indicator of the status of insecticide resistance. Local use patterns are a more sensitive indicator for the emergence of resistance [1, 3].

Environmental Impact

The environmental impact of insecticides, an important consideration for vector-borne disease control, encompasses several components [3, 25]. Vector control generally has a less severe environmental impact than disease effects [1, 6]. When insecticide residues do accumulate, these may eventually affect nontarget species that live outside or near spray zones. The extent of harmful effects depends on the selectivity of the agent employed and the method and precision of deployment. Some insecticides, such as chlorpyrifos, have long residence times and are banned in many countries [5, 23]. Others, such as pyrethroids, dissipate rapidly and, at low doses, are relatively benign with respect to many nontarget invertebrates [8, 19]. Experiments with granular larvicidal formulations (such as temephos) in aquatic environments reveal strong impacts on zooplankton populations, while having little direct influence on microorganisms. Residues in soil, aquatic systems, and wetlands may kill nontarget organisms or have sublethal effects, although the biological significance of these is often unclear. Insecticides applied indoors as residual sprays commonly affect local arthropods; e.g., reductions in cockroach populations have been reported [6, 17]. Although many household insecticides are repellent, the impact of spatial repellents or insecticide vapours on nontarget organisms remains poorly understood [6, 7]. Environmental concerns regarding the effect of insecticides on nontarget organisms, including humans, therefore provide strong motivation to reduce the use of insecticides in general. The use of insecticides in vector control arises from the operation of protected zones designed to prevent exotic pests and disease vectors from entering a (usually) pest-free area [3, 24]. Drawing upon previous procedures developed for Mediterranean fruit fly Ceratitis capitata Wiedemann, such programs have been implemented on a large scale in the USA and Mediterranean countries to protect germplasm importations from pests and VBDs [3, 12]. This has often resulted in massive treatment of citrus fruits, which are widely exported. In some cases, such programs are costly, eliminating much of the value added by treatment to meet quarantine requirements. For example, Ernest J. King & Sons, Inc., spent $2 million on treatment equipment for a 2.5-year federal program involving the treatment of lemons imported from Italy [7, 18]. Such costs often force exporters to seek alternate markets or change their shipment procedures to avoid cold-holding periods demanded by quarantine authorities [18, 19]. Large numbers of insects can survive low temperatures for several days and are transported worldwide in goods and luggage. Airport disinsection remains an important tool for preventing the entry of exotic species. Insecticides are also applied at ports of entry, either as fumigants or vapor treatments to disinfest goods arriving from overseas. Insecticides have also been employed at rollout points on large intercontinental flights [1, 15]. Numbers of exotic mosquitoes have been intercepted as larvae and adults following similar treatments at ports in the USA [1, 12].

Socioeconomic Factors

Financial and sociocultural factors heavily impact the success of control programs, even those supported by hundreds of millions of dollars annually in VBD-endemic countries [1, 23]. Insecticide-treated nets, the most widely employed control tool for a range of VBDs, can cost nearly a month's wages; community-based programs are challenged by labor demands and sociocultural acceptability [2, 8]. Sustained community participation is a critical challenge for local governments that often lack the human and financial capital to maintain vector management systems. Without continuous disposal of water-holding containers and other larval habitats, vector populations quickly rebound to risky levels [1, 7]. The adoption of highly technical interventions, involving laboratory-reared, genetically modified, or infected vectors, can be inhibited by cultural, ethical, and legal concerns through a pervasive lack of knowledge of what entails with complex strategies entail [7, 17]. Public health and sanitary systems that have created and maintained environments conducive to vectors require institutional coordination and political commitment to remediate the problem [10, 20].

Public Health Infrastructure

Vector-borne diseases present a persistent threat to public health worldwide [1]. Mosquitoes transmit multiple infectious organisms, including Plasmodium protozoa, filarial nematodes, and viruses that cause malaria, lymphatic filariasis, dengue fever, yellow fever, Zika virus disease, Japanese encephalitis, West Nile fever, and chikungunya. Vector-borne diseases cause more than 700,000 deaths each year and account for 17% of global infectious diseases [1]. Effective control is essential to reduce vector-borne disease transmission and impact [8]. Vector control is a key strategy for managing mosquito-borne diseases. The global focus on COVID-19 distracted surveillance and control efforts targeted at vectors and vector-borne disease outbreaks. Consequently, dengue increased dramatically worldwide in 2020 and 2021[1, 8]. Vector control requires innovative solutions to overcome challenges presented by insecticide resistance, socio-economic, operational, and environmental constraints, and climate change. Public health infrastructure and resources are fundamental for sustained vector control [5, 18].

Weak infrastructure and inadequate resources limit the quantity and quality of surveillance, training, material, and personnel availability, and community engagement and advocacy [5, 17]. Insufficient infrastructure and resources hinder control programs from successfully implementing actions and sustaining coverage, especially across large geographic areas [7, 13]. Weak infrastructure facilitates vector-borne disease epidemics and widespread geographic dissemination of vectors [4, 13].

Case Studies of Successful Vector Control

Examples of Integrated Vector Management (IVM) illustrate how coordinated and adaptive strategies can mitigate public health risks posed by vector-borne diseases. Malaria control in Tanzania underscores the effectiveness of micro-stratification based on transmission intensity, which enhances planning through targeted interventions [8]. Modelling designs of indoor residual spraying (IRS) programmes in sub-Saharan Africa further informed operational targets for controlling Anopheles vectors in specific districts[5, 17]. In the Philippines, enforcement of existing policies guides vector control, resourcing, implementation, monitoring, and reporting within malaria and dengue programmes [3, 8]. Operational experience identifies principles critical for improved efficiency and sustainability, including micro-stratification, integration within health services, multi-disease approaches, involvement of local authorities, and community empowerment [14]. Insecticide management also plays a crucial role. Case studies from six countries across Asia and the Middle East reveal challenges in managing resistance, procurement, safety measures, storage, waste disposal, and regulations, especially in low-income settings. Heightened institutional responsibility and detailed country-level analysis are needed to enhance vector control and optimize insecticide usage [9].

Malaria Control in Africa

Malaria remains one of Africa's most serious public health problems, accounting for 300–500 million clinical cases and between 1 and 2 million deaths annually [15, 20]. The disease constitutes a major barrier to the region's socio-economic development, with over 70% of the population at risk of infection and malaria-related ailments accounting for 30% of all outpatient visits. Pregnant women and children under five years of age are especially at risk [16]. The Kenyan government has mounted an ambitious effort to combat malaria through a 10-year National Malaria Strategy aimed at reducing malaria-related illness and death by 30% by 2010[5, 18]. Malaria transmission in agricultural ecosystems constitutes a complex process involving interactions among the human host, mosquito vector, the environment, and socio-economic factors [1, 12]. More than 80% of the respondents in some communities were aware of the major breeding sites of mosquitoes around their homes, while support for the enforcement of environmental sanitation was high [16]. About 81% of the respondents used various forms of protective measures to prevent mosquito bites, the use of treated bed nets and insecticide sprays being the most common[5, 19]. Individual malaria control methods have been shown to exert different degrees of reliance on the awareness of the end user; those that alter the environment or target autonomous mosquito behaviours tend to be more reliable and sustainable [16]. Alternative options can also be deployed to either complement or supplement existing methods.

Dengue Control in Southeast Asia

Dengue is the fastest spreading vector-borne disease, causing significant economic and health burdens worldwide [1, 17]. Its main vector, Aedes aegypti, breeds in water containers found in the domestic environment; the resulting association with rapid and often uncontrolled urbanization and human behavior facilitates the emergence or resurgence of outbreaks and creates complex transmission patterns that seriously challenge efficient control strategies[5, 17]. Consequently, vector control relies heavily on community engagement and intersectoral partnerships with the involvement of households and institutions, and more recently has focused on targeted interventions directed at key container types, insecticide-treated window curtains, and container covers [9, 10]. The need to integrate environmental management and mobilize communities to reduce mosquito proliferation and dengue transmission has been consistently highlighted [1, 23]. Within this framework, behaviour change interventions that seek to improve knowledge of dengue and routine participation in vector control have become central to reducing sites of potential Aedes development. Dengue is one of the world's most threatening mosquito-borne diseases, with an estimated 390 million new infections occurring annually, of which 96 million are symptomatic [2, 20]. The main vectors of the dengue virus are Aedes aegypti and Aedes albopictus. Four antigenically distinct dengue serotypes circulate in human populations. Infection with one serotype leads to lifelong immunity to that serotype and only partial and transient cross-immunity to other serotypes. Serotype cross-reactivity results in an increased risk of severe dengue and death with subsequent heterologous serotype infection. Neither a specific treatment nor a vaccine with full efficacy exists [6, 7]. In the absence of an effective vaccine, control measures are urgently needed. Vector control is currently the most common strategy because it poses minimal environmental risk and requires limited resources. The three main approaches for controlling dengue vectors are chemical, environmental, and biological methods. Chemical methods involve insecticide spraying and the destruction of breeding sites with larvicides. Environmental methods focus on the elimination of standing water and waste management [3, 24]. Biological control targets the immature stages with natural predators, pathogens, or growth regulators. Novel methods use genetically modified mosquitoes or mosquitoes infected with Wolbachia bacteria that are unable to transmit dengue virus, with the latter receiving increased attention because of the potential for a self-sustaining intervention [3, 25].

Zika Virus Response

ZIKV is the latest emerging vector-borne pathogen to threaten a significant public health emergency at the global level [1, 15]. The international coordination of experts in different fields of biomedical research serves as a fundamental tool to enhance knowledge on the epidemiology of this virus and allows the prompt design and administration of prevention and control strategies [3, 18]. Outbreaks of ZIKV have recently been reported from many regions in India; therefore, it may become a potential public health threat soon. To minimize this impact, it is necessary to understand its etiopathogenesis and establish adequate early warning systems and preventive and control measures [4, 22]. The development of genetically modified mosquitoes that are unable to reproduce and capable of outcompeting the wild phenotype will be helpful against this threat. In addition, herbal mosquito-repelling products, which are safe for use by humans of all ages, may be utilized to control ZIKV spread. Health workers should adopt adequate sanitary measures to prevent infection and further transmission of the virus and thus require proper protection before blood and organ donation [7, 9]. Other modes of ZIKV transmission require further exploration, as a better understanding of these routes would help develop more effective prevention and control strategies. Pregnant women living in or travelling to areas endemic for ZIKV infection should consider postponing their visit [8. 17]. Moreover, particular attention should be paid to better dissemination of epidemiological information to increase the awareness of the population about the possible clinical outcomes of the disease [8, 24]. To improve control strategies, researchers must quickly share their data on mosquito control throughout the world. Collection of detailed information on ZIKV cases will provide further opportunities to improve our current understanding of vector–virus relationships and allow a rapid and effective response to virus spread [2, 21]. The urgent development of an effective vaccine for prophylactic use should be a priority for the global biomedical community.

Innovations in Vector Control

Vector control, the suppression of population density or the interruption of human-vector contact, is primary in reducing vector-borne diseases [4, 18]. Conventional approaches, those of chemical, biological, environmental, and genetic control, have been consolidated over decades and remain generally effective; however, maintaining such success has become increasingly difficult in recent years. Notable challenges include the continuous emergence of insecticide resistance, the deterioration of public health infrastructure, climate change, globalisation, urbanisation, and the recent effects of the COVID-19 pandemic [1, 7]. Research on this subject is thriving, with the intention of mitigating these issues. This synthesis highlights briefly the dominant vector control strategies and their prominent hurdles before an overview of promising prospective innovations, which might direct future investigations towards the control of vector-borne pathogens [9, 21].

Novel Insecticides

The recurrent emergence of arbovirus epidemics has prompted the pursuit of new insecticidal products with innovative modes of action [1]. In addition to new active ingredients, emerging classes of chemicals include binary mixtures (e.g., neonicotinoids plus pyrethroids) and chemicals repurposed from agricultural or public health applications. Alternative agents such as entomopathogenic fungi, plant-based insecticides, and aerosolised toxins, alongside new active ingredients, are in initial screening phases [1, 20]. For example, Anopheles spp. Mosquitoes resistant to several insecticide classes remain susceptible to the novel glypyridine compound broflanilide. LEED methods ("lethal…everything exposed") offer the potential to reduce operational costs and sidestep many challenges associated with conventional intervention strategies. Although currently in early research stages, formulation of novel active ingredients into LEED approaches represents a major opportunity for the next generation of vector control strategies [2, 22].

CRISPR and Gene Drive Technologies

CRISPR gene editing technologies show promise for controlling the populations of arthropods that serve as vectors for human pathogens [3, 19]. Gene-drive systems combine CRISPR gene drives with homing mechanisms to increase the likelihood of inheritance for particular alleles. This allows researchers to introduce deleterious mutations that reduce the fertility or viability of the target species, which in turn leads to population suppression. The efficiency of this approach was demonstrated in 2014 when Italian researchers used a gene-drive system to convert a heterozygous female fruit fly to a homozygous state in over 95% of offspring [3, 23]. The development of countermeasures to halt or reverse unintended outcomes is essential before approving CRISPR-based autonomous homing gene drives for biocontrol [1, 20]. Most control systems aim to stop or reverse drives but often do not address the environmental persistence of transgenes, which depends on the associated fitness costs. For instance, reversal drives such as immunizing reversal drives (IRDs) can be effective; however, high fitness costs may lead to their removal from populations [6, 25]. While immunizing reversal drives require further laboratory testing, anti-drive systems that rely on protein-protein interactions have demonstrated better performance in modeling studies, though additional empirical evaluation is needed[8, 18]. Biodegradable gene drives incorporating self-elimination mechanisms offer a theoretical solution to transgene persistence but remain largely untested. Many gene-drive strategies focus on population suppression by introducing fitness loads or skewed gender ratios; nonetheless, the evolution of resistance remains a major concern [7, 24]. Spatial or temporal limitation of drives may mitigate resistance but often necessitates multiple releases. Moreover, natural genetic elements such as transposons and evolutionary responses involving small RNA pathways can also facilitate resistance to Cas9-based systems [1, 20]. Given the complexity of these challenges, ongoing exploration of diverse control strategies is critical to address the full spectrum of gene-drive-associated issues [5, 25].

Smart Traps and Surveillance

Numerous mosquito-trap prototypes have been commercialized to attract various species [2, 9]. Specific lures motivate female mosquitoes to enter traps, offering an alternative to hazardous chemical spray catches. Attractants activate the taxonomic host-seeking cascade by odour-baiting, heat, water vapour, light, colour, CO_2, or gravid strategies [8, 25]. Their independent or combined contributions vary among taxa and environmental settings. Carbon dioxide is a near-universal cue for vertebrate blood-feeders and is effective when combined with odourant lures. Conventional odour baiting depends on synthetic blends replicating vertebrate skin odour or natural sources, but carbon dioxide supply is costly and logistically difficult. Cheap alternatives have been evaluated and optimized, such as human-worn cotton socks and other stockings; yeast-sugar fermented mixtures, and varied pulsed and diffusive release formulations. GPS data logging associated with site coordinates generates geospatial abundance maps, enabling site-specific information on population-scale behaviour and distributional patterns [1, 24]. KwikPoint®, a dedicated smartphone application (currently developed on the Android platform), facilitates repository contents. The phone's GPS functionality automatically logs trap locations, prompted by embedded Web messages, and mosquito abundance data can be uploaded onto a centralized remote Web server. Human population movement is a critical variable frequently unaccounted for when interpreting entomological data for epidemiological surveys and intervention evaluation [1, 25]. Periodically, monitoring malaria transmission intensity in parallel with sickle-cell genotypes is explicitly designed to limit variations due to host genetics 21. Important mosquito species for epidemiological studies and control campaigns can be custom-configured to optimize performance at any given site [1, 16].

Community Engagement and Education

Local communities are an essential part of the vector control process and require continuous participation and engagement to establish sustainable public health and sanitation practices [1, 15]. The availability of clean water and proper waste disposal are critical components of community participation that depend on the availability of government resources. Large-surface water catchment methods and control initiatives aim to significantly reduce unnecessary container water usage and the production of container-based artificial breeding sites [8, 25]. Local government plays a crucial role in allocating appropriate resources to remove or recycle containers that may accumulate water and serve as vector breeding grounds [1, 9]. These combined efforts must be effectively supported by comprehensive community education and awareness strategies to promote behavioural change. There are critical knowledge gaps limiting general comprehension of diseases such as Zika in affected areas, which hampers the effectiveness of health providers and community engagement programmes. Extensive education and communication campaigns must be implemented to foster widespread behavioural shifts that are integral to the success of vector control strategies [22]. Community perceptions of vector control methods form a fundamental part of the success or failure of mosquito-control programmes such as ovitraps, which require extremely high coverage to prevent even a small number of mosquitoes from transmitting disease [7, 19]. Communities should be thoroughly informed about new control measures and strongly encouraged to actively participate in vector control efforts. Within Trinidad, the use of assessment tools among selected groups of individuals facilitated the acquisition of valuable information concerning community members' knowledge, practices, and perceptions of yeast-interfering RNA (yRNAi)-baited ovitraps before their deployment in a successful vector control field trial[6, 22]. Following prenatal village tours intended to enhance knowledge of the new technology, interview participants exhibited greater familiarity with the yRNAi-ovitraps than those from unexposed villages; however, these interviews only comprised a small, non-representative sample predominantly consisting of older individuals. Community forums and one-on-one household interviews, conducted post-exposure, provided immediate opportunities to address concerns and identify previously unrecognized issues. These engagement tools also enabled comparative analyses of attitudes before and after direct interaction with the product [23]. The ethical challenges associated with the introduction of new interventions are expected to expand as novel vector control methods are developed [8, 23]. The World Health Organization underlines the need for cautious administration of these technologies when social determinants such as age, gender, education level, and socio-economic status may influence individuals' decisions to participate in field trials or vector control treatment programmes [11, 25]. Vector management frequently depends on collective community actions and widespread consent, underscoring the vital role of engagement and education in the overall vector control strategy [1, 23].

Role of Local Communities

Local communities have a critical function. The most successful vector-control operations engage communities through understanding their requirements, the social context, trust and relationship-building, social mobilization, empowerment, identity, integration with local organizations, participatory approaches to engaging with the community, and locally recruited staff [14]. Since the late 1990s, programs have focused on decentralization and community engagement to enhance sustainability [22]. Active community participation and local awareness of risk factors should be integral components of effective, sustainable, and area-wide integrated vector management programmes. In the Philippines, strategies contributing to improved efficiency and sustainability of vector control operations were micro-stratification, integration of vector control within the health sector, a multi-disease approach, involvement of local authorities, and empowerment of communities [14, 22]. Capacity building on situational analysis and vector surveillance, thus requires attention through national policy and guidelines. In addition, vector-control efforts depend on effective community participation and local awareness of risk factors.

Public Awareness Campaigns

Public awareness and sustained education campaigns remain one of the most important aspects of any vector-borne disease programme. Long-term community participation is required for interventions to succeed [3, 21]. Enhanced knowledge of both vectors and diseases can support community engagement and the efficient implementation of vector control programmes. The importance of awareness and education has been highlighted in numerous outbreaks and epidemics, such as Zika during the Olympic Games in Brazil or in dengue programmes worldwide. Furthermore, detailing methods of prevention can also encourage behaviour change and enable communities to take ownership of control programmes in the long term [4, 22]. Maintaining awareness over time is crucial, given the prevalence of asymptomatic cases in some vector-borne diseases, which means the community can feel less threatened. Awareness and education programmes also promote correct diagnosis and good case management among medical personnel [5, 18]. Moreover, field staff perceptions of vector control campaigns must also be considered to ensure the operationality of programmes on the ground and social acceptance of the methods implemented. In the case of emerging tools or new approaches, awareness and education are likely to take a greater role in promoting uptake, acceptance, and trust towards programmes; in some cases, it can help to overcome resistance among communities, which may be due to socio-political or religious reasons [14, 24].

Global Policy and Vector Control

The Global Vector Control Response represents the WHO's latest approach to tackling mosquito-borne infections and was adopted in 2017 to strengthen integrated vector management to prevent the global spread of vector-borne diseases [9, 18]. IVM entails using evidence-based methods both singly and in combination to improve deployment, efficacy, resistance management, and sustainability, and to minimize health and environmental risks. Continued international collaboration has put vector control in the spotlight for gaining additional funding [1, 15]. Development of new tools that provide a means of overcoming the remaining challenges will be essential to reducing global transmission of vector-borne diseases [13, 19].

World Health Organization Guidelines

In response to the emergence of vector-borne diseases, the World Health Organization published guidance aimed at integrating control approaches within health systems through strengthening policy frameworks, multisectoral collaboration, vector control tools, and capacity-building [9]. Further initiatives seek to unite the relevant scientific and policy communities to transform vector control globally over the next decade. A global survey conducted over 2010–11 to assess pesticide management in the control of vectors of malaria and other major vector-borne diseases revealed that basic policies involving levels of support and engagement varied widely between the 113 countries surveyed[9, 11]. Although many countries had adopted the WHO-recommended Code of Conduct on Pesticide Management, nearly half had no pesticide use legislation. Countries in most regions lacked pesticide quality control, and around a third had no guidelines or regulations on either the public or private sector of occupational or environmental safety. Procurement practices often did not comply with legislation or lacked policy [3, 17]. Consequently, the survey flagged a need to implement relevant WHO recommendations to improve pesticide management, raise the effectiveness of application, minimize negative impacts, and support the global drive toward strengthened capacity in vector control [24].

International Collaboration Efforts

Since its first adoption at the World Health Assembly in 2005, the International Health Regulations (2005) have provided a legal framework for global health security. These regulations require countries to develop and maintain a national capacity to detect, assess, notify, and report public health events, thereby establishing a mechanism for monitoring potential international public health threats [1]. The rapid spread of vector-borne diseases (VBDs), such as the Zika virus, highlights the pivotal role of international collaboration for the prevention, control, and mitigation of new public health challenges [25]. The World Health Organization (WHO) has launched an important program for the control of emerging VBDs that focuses on identifying efficient strategies and innovative tools for epidemic prevention; harmonizing various regional initiatives; complementing and supporting member states' efforts; collaborating across sectors and disciplines; and building a global network of public health experts and practitioners. Intersectoral collaboration is a key factor for reducing VBD transmission and vector densities [25]. The Prevention and Control of Zika Virus Infection Capacity Rapid Assessment Framework was specifically designed to assess in-country operational capability and capacity to prevent and/or control Zika virus transmission through VBD prevention and control strategies. This tool also facilitates in-depth discussions among key stakeholders, thereby promoting multisectoral collaboration and the development of operational plans for the Prevention and Control of Zika Virus vector transmission [1].

Future Directions in Vector Control

Research priorities must address insecticide resistance monitoring and management, improved delivery systems for vector control strategies, and the development of novel tools based on entomological and epidemiological knowledge [1]. The capacity of control programmes remains limited in many countries. Novel interventions are combining approaches, including integrated vector management, and alternative methods, such as Wolbachia bacteria, novel insecticides and formulations, and automated designs for vector surveillance [6, 7]. The goal is to deploy a cost-effective product, which is readily accessible and acceptable in a given setting. Priority must be given to developing tools capable of providing sustainable levels of local control that lead to reduced disease transmission [5, 15]. Predicting the impact of new products is challenging, and quantifying efficacy against epidemiological or entomological end-points remains a key focus [11, 15].

Research Priorities

Research priorities are a critical component of successful vector control, and yet the distribution of worldwide efforts and their appropriate funding remains a challenge [1, 9]. Vector control is a key element in the successful reduction of vector-borne diseases worldwide. Mosquito control campaigns launched in the 1940s and 1950s eradicated Aedes aegypti from much of South America; the economic crisis of the 1980s, coupled with increased insecticide resistance and ineffective public health systems, resulted in the return of Ae. aegypti and disease re-emergence[1, 12]. Systematic larval source reduction is challenging in highly populated areas where cryptic, inaccessible breeding sites exist. During the Zika outbreak of 2015–2016, containers harbouring the immature stages of Ae. Aedes aegypti accounted for <10% of all pupae collected, most of which were discarded receptacles located in the peri-domestic environment. Often insufficiently equipped and understaffed, public health agencies require increased personnel for widening vector surveillance and control operations [1, 7]. The ability to implement effective control interventions rapidly and efficiently depends upon the existence of a robust vector population surveillance system capable of detecting vectors before a disease outbreak, utilising standardised protocols that can be followed at regular intervals [8]. Effective monitoring of mosquito control activities also determines how resources are allocated and which activities continue. Training of future public health officials and the workforce responsible for control measures is a major challenge and requires a multidisciplinary and integrated approach [1, 8, 24].

Funding and Resource Allocation

Adequate funding and rational resource distribution constitute essential components of effective vector control. Nonetheless, a significant dearth of documented financial information on vector control has been noted [8]. Malaria control intervention coverage varies substantially among malaria-prone countries, often failing to extend to the entire at-risk population [14]. Financial resources for malaria control are increasingly constrained, and the costs of achieving universal coverage with control tools, commodities, and case management are substantial. Allocating resources based on local vector ecology and human behavior patterns is imperative [25]. In addition to scarce monetary investments, many endemic countries also face shortages of trained and experienced staff, contributing to limited capacity for effective vector control, particularly in rural or hard-to-access areas [8, 14].

CONCLUSION

Vector-borne diseases continue to exert significant health and socio-economic impacts, particularly in regions with fragile health systems. Although conventional vector control methods have achieved substantial progress, their sustainability is increasingly undermined by resistance, environmental concerns, and limited resources. The integration of innovative approaches ranging from genetic modification to biological control offers new opportunities but must be balanced with ethical oversight and ecological safeguards. Importantly, community awareness and participation remain central to the success of any intervention. A future-oriented strategy will therefore require strengthened public health infrastructure, enhanced research investment, and international collaboration. By combining science, policy, and grassroots engagement, the global community can move closer to sustainable control and eventual elimination of vector-borne diseases.

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