Chapter 18

Exploiting the Potential of Integrated Vector Management for Combating Malaria in Africa

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Additional information is available at the end of the chapter

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Abstract

Integrated Vector Management (IVM) is advocated by the World Health Organization (WHO) as the pivotal platform for vector control. The threat for malaria and emerging and re-emerging vector borne diseases is increasing. However, adoption and deployment of the IVM strategy has been minimal. Though malaria endemic countries are embracing and consolidating the IVM approach, real time entomological data on transmission risk and targeting the right vector with the appropriate intervention is lacking. IVM could be harnessed for circumventing operational constraints for vector control. Herein IVM for combating malaria and other insect-borne diseases is reviewed and ways to maximize its potential and benefits are proposed. IVM promotes operational research for evidence-based, cost-effective and optimally sustainable vector control with judicious integration of available options, improves management of insecticides, and effective mitigation of potential negative health and environmental impacts. IVM enhances institutional arrangements including accountability, collaboration and coordination of stakeholders. IVM will require policies and frameworks to maximize intervention impact; and infrastructure and human resources capacity, community involvement and information sharing, strengthened regulation for registration and quality assurance, procurement, financial management and supply chain management for commodities. However, national health system-based response among stakeholders and political commitment is needed for optimal IVM implementation.

Keywords: integrated vector management, malaria transmitting mosquitoes, insect-borne diseases, strategic planning, operational frameworks, evidence-informed decisions, intersectoral collaboration, capacity building

1. Introduction

Malaria remains the biggest health threat among vector-borne diseases (VBDs) with approximately 214 million annual cases and a related 438,000 deaths occurring worldwide in 2015, particularly in sub-Saharan Africa [1, 2]. Though vector control is a proven approach for controlling and eliminating disease, its continued efficacy is likely to be compromised by a multiplicity of constraints [3]. To mitigate the problem, endemic countries in collaboration with the World Health Organization (WHO) have implemented various vector control tools over the years. The quest by WHO for rational evidence-based vector control approaches can be traced through several conceptual stages as: integrated vector control strategy, 'utilization of all appropriate, safe and compatible means of control to bring about an effective degree of vector suppression in a cost-effective manner' [4]; selective vector control, 'application of targeted, site specific and cost-effective activities to reduce disease morbidity and mortality' [5]; and comprehensive vector control, 'control of the vectors of two or more co-prevalent diseases through a unified managerial structure using similar or different vector control methods' [6]. Until recently, management of some vector control programmes have mostly been vertical in disposition. To maintain the effectiveness of vector control, the integrated vector management (IVM) strategy was established and advocated by the WHO as a pivotal and recommended platform for combating VBDs [7]. As such, vector control programmes in endemic countries are encouraged to adopt, establish and implement national policies for the approach. By definition IVM is 'a rational decision-making process for optimal use of resources for vector control' [8]. The IVM strategy is based on the premise that effective control is not the sole preserve of the health sector but of various public and private agencies, including communities. It uses sound principles of management and allows full consideration of the determinants of disease transmission and control [8].

Effective IVM policies incorporate available health resources and infrastructure, uses methods based on knowledge of factors influencing local vector biology; disease transmission and morbidity, deploys a multi-disease approach, integrates recommended environmental, biological or chemical interventions, often in combination and synergistically, includes inter-sectoral collaboration within the health sector and with other public and private sectors that impact on vectors; engagement of local communities and other stakeholders; and a public health regulatory and legislative framework , and reinforces vector control management systems [7]. To circumvent vector control-related constraints in the face of dwindling public-sector human and financial resources, the WHO provides technical assistance [8] and documents, guidance on policy-making [9], structure for training [10], handbook for IVM [11] and monitoring and evaluation [12] to facilitate implementation processes. Unfortunately, only a limited number of countries have harnessed IVM to operationalize efficacious VBD control. The IVM approach has five key strategic elements: advocacy, social mobilization and legislation; collaboration within the health sector and with other sectors; integrated approach; evidence-based decision-making; and capacity building [7]. Notably, an IVM-based process should be underpinned by operational research and monitoring and evaluation of impact on vectors and disease transmission, cost-effective, encompassing requisite infrastructure, financial resources and adequate human resources to manage and implement vector control [13]. Nevertheless, substantial challenges for implementation exist at national and local levels and operational experience for the strategy is still limited to relatively few countries.

While vector control has potential to control and eliminate VBDs [2], it has been invariably compromised by: the emergency of insecticide resistance in disease vectors coupled with the lack of sustainable financial resources to sustain control programmes [7], scarcity of personnel with requisite skills and minimal or lack of collaboration between health and other relevant sectors (e.g. infrastructure development, agriculture, environment and educational sectors) to effectively monitor and manage it [5]. Other constraints include residual and outdoor malaria transmission, nominal real-time entomological and epidemiological information to understand transmission risk and to target the right vector with the right control method at the right time; environmental, socio-cultural, socio-economic, technical and programmatic setbacks; weak health systems; limited access to health services; lack of pesticide and resistance management plans; weak planning and coordination amongst disease control programmes. Equally, population increase, returnees, internally displaced and nomadic behaviour of people preclude effective deployment of interventions, particularly in emergencies. The situation is further aggravated by the absence of guidance on IVM in humanitarian emergencies and exclusion of emergency situations in the WHO Handbook for IVM [11].

The need for strengthened human and infrastructural resources to improve vector control has been a topical issue deliberated upon at various forums [14]. Accordingly, appeals and proposals to address inherent challenges have invariably been made to bilateral and multilateral organizations, funding and implementing partners [15]. Nevertheless, limitations that are operationally crucial and with potential to compromise effective programming locally still remain minimally addressed. Though highly divergent at country levels, in the face of shrinking resources, the need to adequately circumvent these pertinent shortcomings is obvious and inevitable. Well-implemented IVM provides a potential platform that could be exploited for enhanced entomological monitoring and surveillance, strategic insecticide resistance management (IRM) planning and rational VBD control and elimination of transmission [16]. In this chapter, an attempt is made to critically review and appraise information on malaria vectors and other insect-borne diseases that could potentially be controlled in tandem, using available tools and management strategies for their control and bringing to the fore some of the pertinent challenges experienced in operational settings. A framework of policies and strategies to facilitate the implementation of the IVM approach is presented and will accentuate coordinated responses amongst stakeholders and political commitment for effective policy execution within the context of national health systems.

2. Methods and literature search strategy

The need to streamline vector control efforts for mosquito-borne diseases, particularly malaria is the case for this review describing a 'literature overview' about implementation of IVM for combating diseases. Information sources for this review included all available data and accessible archived documentary records on malaria vector control. Structured literature searches of published, peer-reviewed sources using online scientific bibliographic databases were utilized to gather pertinent data from endemic countries. This was conducted via systematic literature search of Library catalogues and online electronic databases, particularly PubMed [17], WHO Library Database [18], Google Scholar [19], African Journals Online [20], Armed Forces Pest Management Board [21], and research for life database HINARI [22] were used to search for the relevant literature. All digital electronic database searches for peer-reviewed, published work used a combination of key search terms: (1) complex of *Anopheles* malaria vectors and one of the following terms; (1) 'IRS' and IVM; (2) ITNs/LLINs and IVM; (3) LSM and 'vector control' and 'prevention' and 'surveillance'; (4) malaria epidemiology; (1) and (4); (2) and (4); and (3) and (4); vector control, epidemiology, malaria, house improvement, *Bacillus thuringiensis* var. *israelensis* and *Bacillus sphaericus*, biological control for malaria control and innovative malaria vector control tools, dengue fever, chikungunya, yellow fever, lymphatic filariasis, Western equine encephalomyelitis, St. Louis encephalitis virus (SLE), human African trypanosomiasis, South American trypanosomiasis (Chagas disease), leishmaniasis, onchocerciasis, Zika and trachoma. Literature was also reviewed from settings with similar framework strengthening approaches. Reference sections of all relevant articles were also reviewed to identify more literature. Additional non-peer reviewed literature including strategic and implementation plans and annual reports were examined for information related to the subject. The inclusion criteria considered all manuscripts and publications in English language that report on malaria vector control and IVM. The literature was reviewed and applicable research findings and key concepts from other countries in different regions were considered for inclusion and translation into this framework.

3. Important insect-borne diseases and responsible vectors

The threat of malaria [14] and emerging and re-emerging VBDs such as dengue fever [23], chikungunya [24], yellow fever [25] and lymphatic filariasis [26], most of which are mosquito-borne, is increasing. Vector control need assessments for IVM conducted in several countries indicate the presence of multiple VBDs with divergent endemicities and spatial distribution. Globally, there are many important vectors of malaria parasites such as *Anopheles gambiae* s.s., *Anopheles arabiensis* and *Anopheles funestus* in Africa; *Anopheles stephensi* and *Anopheles culicifacies* in Asia; *Anopheles albimanus* and *Anopheles darlingi* in the New World tropics; and *A. labranciae* and *Anopheles sacharovi* in Europe. Detailed descriptions of the updated global distribution of malaria vectors are provided elsewhere [27, 28]. Many species of *Aedes* and *Culex* are vectors of arboviruses that infect various vertebrates, including humans. *Aedes aegypti* is a principal urban vector of the yellow fever virus and is the primary vector of the dengue viruses. *Aedes albopictus* is a primary vector of forest yellow fever and a secondary vector for dengue fever in most regions. Chikungunya vectored by *Ae. albopictus* and *Ae. aegypti* has increasingly been reported [24]. *Culex quinquefasciatus* is a vector of the nematode worms causing lymphatic filariasis (LF) and of several arboviruses. LF is also transmitted by *An. gambiae*, *An. arabiensis* and *An. funestus* mosquitoes in several countries. *Culex pipiens* is the vector of Tahyna virus in Europe, St. Louis encephalitis virus (SLE) in North America, and West Nile virus in several continents. *Culex tritaeniorhynchus* is the primary vector of Japanese encephalitis virus in Asia, and *Culex tarsalis* is the primary vector of Western equine encephalomyelitis and SLE in western North America. *Aedes* (*Neomalaniconion*) *mcintoshi* and related species are important enzootic transmitters of Rift Valley fever virus in Africa [29]. Human African trypanosomiasis is vectored by *Glossina fuscipes*, *Glossina tachinoides*, *Glossina palpalis*, *Glossina pallidipes* and *Glossina morsitans* species of tsetse flies. South American trypanosomiasis (Chagas disease) vectored by *Triatoma infestans*, *Panstrongylus megistus*, *Rhodnius prolixus*, *Triatoma brasiliensis* and *Triatoma dimidiata*. Leishmaniasis (kala-azar) is transmitted by *Phlebotomus orientalis*, *P. argentipes*, *P. papatasi*, *P. longipes*, *P. sergenti*, *P. martini* and *P. celiae* species of sand flies. Onchocerciasis (River Blindness) is vectored by *Simulium damnosum* complex and *Simulium neavei* group black flies in Africa, and *Simulium ochraceum*, *Simulium metallicum* and *Simulium exiguum* complexes in Central and South America. Other commonly endemic diseases include trachoma vectored by *Musca sorbens* bazaar flies [30]. Recently, outbreaks of yellow fever were reported in Ethiopia, South Sudan [31], Zambia [25], DRC and Angola [32]. Notably, the global scale of insect-borne diseases is enormous despite most of them having World Health Assembly resolutions passed on combating them [32, 33].

4. Epidemiological context of malaria

The global burden of malaria remains threateningly high, especially in Sub-Saharan Africa where the disease is endemic in most areas and the region is responsible for about 90% of all malaria deaths globally [2]. The majority of people reside in areas with relatively stable malaria transmission with few inhabiting areas supporting seasonal and less predictable transmission, because of either altitude or rainfall patterns. In areas of stable malaria transmission, the disease burden is highest amongst very young children and pregnant women within the population. An estimated one million people in Africa die from malaria each year and most of these are children under 5-year old [34, 35]. The consensus view of empirical studies, reviews and well informed expert opinion is that malaria causes at least 20% of all deaths in children under 5 years of age in Africa [36]. In most areas, malaria transmission is high, defined as greater than one case per 1000 residents and perennial with substantial seasonal variation in intensity [37]. *An. gambiae* s.s., *An. funestus* and *An. arabiensis* are the main vectors with marked temporal and spatial distribution variation at certain times of the year [38]. Vectorial capacity is high due to abundant rainfall (>2000 mm/annum), elevated year-round temperatures and high humidity [39]. Approximately 98% of malaria cases are due to *Plasmodium falciparum* and is responsible for all severe forms of the disease and deaths [2].

In 1998, the Roll Back Malaria (RBM) partnership revived global malaria control efforts [34]. By 2007, these efforts were invigorated following a call for global malaria eradication [35, 40]. While substantial global progress has been made with 34 countries advancing towards elimination, 64 countries remain in the control phase, mainly in Africa where malaria remains endemic [2]. Examples of countries that successfully eliminated malaria include: Australia in 1960, Taiwan in 1965, Mauritius in 1998, Morocco in 2002 and the United Arab Emirates in 2007

[41]. Between 2000 and 2010, malaria mortality rates fell by 26% globally and by 33% in the World Health Organization (WHO) African Region with approximately 1.1 million malaria deaths averted [2]. Pivotal to these gains, principally in Africa, has been the expansive scale-up of insecticide-based interventions against malaria vectors [42]. From 2008 to 2012, USD 5.83 billion was spent for malaria control in Africa by international donors, and endemic countries scaled up WHO proven interventions including vector control [2]. Generally, attempts to control the anopheline vectors have been limited and intermittent and have had little apparent impact on the huge overall malaria burden [43]. However, the epidemiological trend of malaria disease in the WHO African region has changed significantly over the past years, particularly, due to improved vector control using indoor residual spraying (IRS), long-lasting insecticidal nets (LLINs) and larval source management (LSM), in addition to effective treatment with *artemether-lumefantrine* [43]. There has been a sustained impact on malaria disease burden, evidenced through the reduction in the morbidity and mortality in Namibia, Swaziland, Botswana and Eritrea thus paving the way for them to potentially achieve elimination [44]. However, progresses made in the last 50 years in restricting the geographical areas affected by malaria are being eroded recently, due to changes in land use, global climate changes, armed conflicts/movement of refugees, international travel and emergency of insecticide-resistant vectors.

Vector control is the only available intervention able to reduce transmission at the inception stages of malaria elimination and plays a pivotal role during the attack phase [41]. Vector control remains vital in knocking out the remaining foci of transmission during the later stages of elimination; post-elimination, its role is reducing outbreak risk and as a defence against reinvasion [41, 45]. However, transmission-reducing interventions must be cognizant of behavioural and bionomic attributes of the local vector species including the geography and epidemiology of the malaria foci to be attacked. Therefore, the formulation of plans of action for vector control activities within the malaria elimination strategy should take this information into consideration [45, 46]. The attack phase will aim at maximum intensity and complete coverage throughout to interrupt transmission entirely using selective IRS and universal coverage with LLINs for utmost impact [41, 47]. Nevertheless, there is need to guard against potential challenges such as technical and operational obstacles, procurement, forest malaria, human resource, sustainability, limited data on vector bionomics, insecticide resistance in malaria vectors and gradual declines in both the technical quality of spraying operations and acceptance by target communities. In this regard, capacity building will be critical for successful delivery and effectiveness of the vector control programme [41, 47]. Currently, the global technical strategy for malaria is prioritizing vector control and surveillance. New strategies for vector control are emphasizing IVM [48].

As countries pursue malaria elimination, with strong indications that many, will achieve their goal, IVM approaches will be critical. In countries with well- established IVM, intensive health promotional campaigns and provision of necessary materials have resulted in active participation of communities in vector control activities [44, 49]. To best achieve set goals, an integrated approach in controlling the diseases is recommended wherever feasible given the endemicity overlaps and transmission similarities of some VBDs. This requires adherence to

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all the five key strategic elements of the approach. Recognizing that the IVM approach has been adopted and implemented as the main platform for vector control that include deployment of IRS and LLINs supplemented by LSM [49, 50], there is need for countries to set out to update, revise and widen the scope of their IVM strategies, because of increasing malaria transmission and challenges in vector control. However, the most useful and feasible options for IVM to be applied to the IVM frameworks are: capacity building, integration across diseases, different sectors and communities, evidence-based approach, and collaboration within the health sector and other sectors [42]. This is critical and on effective and efficient deployment of existing and new vector control interventions, to generate and share evidence on integration of all vector control tools and to work with all RBM partners to build entomology and vector control capacity in endemic countries.

5. Rational for integrated vector management

More than half of the world's population is at risk of VBDs, and over one billion people are infected and more than one million die from these diseases annually [1, 2]. In tropical and subtropical regions, climate is most favourable to major VBDs. High diversity of vector-species complexes has the potential to redistribute themselves to new climate or intervention-driven habitats leading to new disease patterns [3]. Up to now, effective reduction of VBDs burden has primarily been ascribed to well-planned and implemented vector control [48], nevertheless, its full potential benefits have not been exhaustively exploited due to limited capacity to manage and deploy vector control; nominal collaboration between infrastructure development and the health sectors; and the detrimental effects of insecticide resistance in disease vectors [51]. To this effect, a Global Strategic Framework setting out the principles and approaches to IVM was developed by WHO [7, 48]. Though IVM forms the cornerstone of contemporary efforts for the prevention and control of VBDs, the approach has only been operationally harnessed in settings with relatively well-established health systems [44, 49]. Only 62% of 113 endemic countries globally and 53% of countries in Africa have national IVM policies and implemented the strategy [52]. IVM has been prompted in part by limited knowledge about deployment in post-conflict settings, where delivery structures are lacking or less developed; very little efforts towards integrating control of multiple VBDs and use of various tools with vector control targeting a single disease and are not fully integrated into health systems, thus compromising their sustainability.

Despite developing multiple global strategies to combat VBDs with renewed emphasis on vector control, high rates of morbidity and mortality are still ascribed to malaria [2, 7]. Vector control need assessments have demonstrated a variety of key factors that undermine the effectiveness of vector control, including: sub-optimal choice or improper timing of interventions and subsequent waste of valuable resources resulting from inadequate capacity for evidence-based decision-making to guide vector control strategies at national, regional, district and community levels; the effect of climate change, environmental degradation and urbanization on malaria and other VBDs, necessitating an adaptive management approach to vector control underpinned by local evidence; lack of collaboration and coordination with other pertinent sectors such as agriculture, industrial works and construction including communities, culminating in limited awareness of the consequences of their actions on the incidence of VBDs; the development of resistance that could potentially undermine effectiveness of insecticide-based vector control efforts [53]. The Stockholm Convention on Persistent Organic Pollutants (POPs) [54] and World Health Assembly resolution WHA50.13 [55] call on countries to design sustainable strategies for vector control. These opportunities, coupled with the presence of arboviral diseases also transmitted by mosquitoes, substantiate the need for an IVM approach to vector control and the development of guidelines that apply, in principle, to all VBDs but focus mainly on malaria control. The IVM strategic plans would require regular adaptation to changes in local eco-epidemiological or socio-economic conditions. IVM provides a unique opportunity to develop cross-disease control programmes, thus facilitating generation and establishment of entomological and epidemiological baseline data for future tracking of performance of interventions. The IVM also plays a pivotal role in mitigating the impact of resistance on vector control interventions as part of resistance management approaches and their inherent effect on control tools [53].

6. Malaria vector control interventions

The arsenal for insecticide-based contemporary malaria vector control is unnervingly limited to a small number of insecticide classes. Furthermore, extensive exposure of malaria vectors to insecticides eventually selects for resistance to them. This necessitates thorough appreciation of available chemical classes, their mode of action, and resistance mechanisms to facilitate utilization of chemical control either in isolation or as part of an IVM approach [56]. Insecticides are classified into four main classes according to their chemical structure. These include chlorinated hydrocarbons (organochlorines) that act by inhibiting the normal functioning of the nervous system. Examples encompass DDT and its analogues that act on the sodium channels of the nerve membrane, benzene hexachloride (BHC) and cyclodienes such as dieldrin acting on the GABA receptors. These insecticides are cheap and easy to manufacture, but their persistence in the environment, wildlife and humans has reduced their use drastically [56]. The second class comprises phosphorothioate insecticides (organophosphates) that include fenitrothion, malathion, pirimiphos methyl and temephos. These insecticides act by binding the enzyme acetylcholinesterase at the nerve junction, and thus commonly called cholinesterase inhibitors. Once bound, this enzyme can no longer remove acetylcholine from the nerve-membrane junction, and the nerve continues to fire in an uncontrolled manner, eventually leading to paralysis and death of the insect. The third class consists of carbamates that have a similar mode of action to that of phosphorothioate insecticides, but they are used in their insecticidally active form as opposed to organophosphates that are invariably administered as the insecticidally inactive phosphorothioate. Examples of carbamates used in vector control are bendiocarb and to a limited extent propoxur. The fourth class is referred to as pyrethroid insecticides. Examples of pyrethroids are deltamethrin, lambda-cyhalothrin and permethrin. Pyrethroids were developed from insecticidally active components of pyrethrum flowers (pyrethrins). These insecticides act in exactly the same way as DDT and its analogues.

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Their lack of persistence makes them good, safe 'knock-down' agents, and they are often still used in aerosols, frequently with the Monooxygenase synergist piperonyl butoxide, which increases their insecticidal activity and reduces their cost. Other insecticides include: insect growth regulators (IGRs) which are compounds that act on the highly species-specific insect hormonal systems (juvenile hormone) that control moulting and metamorphosis. Examples of IGRs are pyriproxyfen and buprofezin; and chitin synthesis inhibitors (benzoylphenylureas) that interfere with the formation of chitin, a major constituent of the exoskeleton of insects. An example of this chemical group is diflubenzuron. The other group involves bio-rationals (bacteria pathogens) that produce toxins capable of disrupting the midgut lining of mosquito and blackfly larvae. The toxins produced by bacteria such as *Bacillus thuringiensis* var. *israelensis* and *B. sphaericus* can be considered as insecticides although they are usually regarded as biological control agents. Detailed descriptions of contemporary and innovative malaria vector control approaches are elaborated elsewhere [57, 58]. A summary is presented below:

6.1. Chemical control

The control of arthropod-borne diseases is anchored by vector control, personal protection and community participation as key WHO strategies. In this regard, vector control aims to reduce and/or interrupt transmission of malaria by preventing human contact with malaria-bearing mosquitoes, reducing the longevity of adult mosquitoes, eliminating breeding sites or killing the mosquito larvae [59]. Contemporary interventions for malaria vector control and elimination encompasses: effective indoor residual spraying; community-wide coverage and use of LLINs; LSM interventions where applicable; and window screens, protective clothing, repellents, etc. The use of IRS and LLINs remains the mainstream malaria vector control tools [60, 61]. Their efficacy has been evaluated widely in different epidemiological settings [62] at community-wide levels [63, 64] and experimental field trials [65, 66]. In reducing abundance and infectivity of malaria vectors, IRS and LLINs reduce overall transmission and confer community-wide protection to all individuals [65], albeit with variation in responsiveness amongst vector populations. Evidence is mounting that combining IRS and insecticide-treated nets (ITNs) affords enhanced protection to exposed populations compared to using one method alone [67]. As such, their deployment together in high malaria risk areas has been advocated [65, 68, 69]. However, the optimal policy for the co-implementation of the two interventions still remains to be determined. Moreover, the development of insecticide resistance in malaria vectors remains a major cause for concern and an increasing threat to these efficacious interventions [70]. Given the inherent diversity in the responsiveness of malaria vectors to control, the core interventions can be supplemented in specific locations by LSM strategies, e.g. larviciding with temephos, biological control and environmental management (EM) in the context of IVM [71].

6.2. Environmental management

The environment plays a particularly important role in determining the distribution of VBDs. Factors that are critical to the survival of different species of disease-carrying vectors include water and temperature, other factors such as humidity, vegetation density, patterns of crop cultivation and housing. In this regard, managing the environment of the vectors that transmit diseases can be harnessed for controlling VBDs. Environmental management (EM) methods that are particularly applicable to malaria may include destruction of breeding sites by drainage, filling, impounding, or channelling streams and rivers into canals or by altering the vegetation and shade characteristics of the sites favoured by the vectors. However, it should be noted that different species of mosquitoes have distinct larval and pupal water quality requirements. The basic definition of EM for vector control is 'the planning, organization, carrying out, and monitoring of activities for the modification and/or manipulation of environmental factors or their interaction with humans with a view to preventing or minimizing vector propagation and reducing human-vector-pathogen contact' [72–75]. Owing to extreme lack of resources and dependency of vector control programmes on insecticide based interventions, EM has not been widely adopted in Africa, where it could potentially have the greatest impact on vector-borne diseases. However, EM should be part of integrated control programmes devoid of net economic drain on individuals of the community. Notably EM practices have potential to adversely affect the flora and fauna of an area [76], necessitating consideration of environmental impact assessments during the planning stage. Several important species of *Anopheles* that serve as vectors of malaria are able to breed in paddy fields. An environmental control method employed successfully in several countries to control mosquitoes breeding in paddy fields is intermittent irrigation. Intermittent irrigation successfully controlled the malaria vector *Anopheles labranchiae* in rice growing regions of Portugal, the malaria vector *Anopheles sinensis*, and some members of the *An. culicifacies* complex in India [77]. A number of important mosquito species breed in the brackish water of coastal marshes. These include: *Anopheles melas* and *Anopheles merus* in Africa; *An. sacharovi* around the Mediterranean; and *An. albimanus*, *Anopheles aquasalis* and *Anopheles grabhamii* in the Americas [78]. One approach to controlling mosquitoes breeding in salt marshes is to drain the marsh and remove the breeding sites [79]. This method, particularly marsh alteration by ditching, is now largely abandoned for more environmentally friendly methods of control. The other successful approach was exclusion of salt water, which prevented marshes from becoming brackish. Though not universally applicable, this method was effective in controlling *Anopheles sundaicus* in Malaya and *An. sacharovi* in Italy [80]. Some mosquito species, such as *An. albimanus*, can breed in fresh water as well as in brackish water, and the existence of fresh water in marshes may provide the water quality required by local fresh water-breeding vectors. All future salt marsh mosquito control programmes based on EM will, therefore, have to be aware not only of the effect that mosquitoes have on people living in and around the salt marsh but also of the impact that any proposed measures will have on salt marsh ecosystems. Environmental methods for vector control in water impoundments, such as the damming of rivers and streams, and the construction of irrigation systems, can dramatically alter the environment both in and around them. In particular, they can provide or enlarge the environment suitable for the breeding of major invertebrate disease vectors. This is exemplified by the Tennessee Valley Authority project that resulted in an outbreak of malaria caused by the vector, *Anopheles quadrimaculatus*, breeding in them [81]. It should be noted that the environmental methods to prevent malaria may also include elimination of breeding sites by drainage or by applying locally grown plants [78].

6.3. Biological control

Biological control involves the reduction of a target vector population by a predator, pathogen, parasite, competitor or toxin produced by a microorganism. Biological control usually has the advantage, over conventional broad-spectrum insecticides, of target host specificity with corresponding little disruption of non-target organisms in the environment. It is also capable of providing long-term control after a single introduction. The fundamental principles of biological control encompass two aspects: population ecology and mosquito ecology. In population ecology, most populations do not fluctuate around their carrying capacity that the environment can support due to the presence of other mortality factors. Mortality factors are mostly classified as density dependent (DD) or density independent (DI). With DD factors, mortality increases as the population becomes denser and decreases as the population becomes less dense. Density-dependent mortality factors tend to regulate a population around an average size and to resist change to that average size, and are characterized by mortality that is not proportionate to the population density. Therefore, with both DD and DI mortality, biological control will be successful only if the vectorial capacity of the adult vector population declines to an acceptable level [82].

As regards mosquitoes, ecology differs considerably by species, although some generalizations can be made. Mosquito populations are often characterized by rapid increases and precipitous declines. The females are highly fecund, and most species have short generation times under tropical conditions. Thus, most populations can quickly increase when the breeding season begins or rapidly rebound after a catastrophic event. Furthermore, the adults of many species disperse well and the females quickly re-colonize habitats. Larval habitats are diverse, ranging from ephemeral to permanent, from artificial to completely natural, from hoof prints to rice fields, although most species occupy only a well-defined subset of these breeding sites. Different mortality factors predominate in different habitats. DD factors in mosquito populations include predators in permanent ponds of rice fields, overcrowding and competition and, more rarely from predators or pathogens in small-containers, such as tree holes. DI mortality factors such as flooding, temperature extremes and desiccation can be important in any of these habitats. However, the ideal mosquito biological control agent probably does not exist, as it should respond to any vector population increase by rapidly colonizing its habitat and quickly producing numerous progeny. It should be able to efficiently find all vectors, survive periods of mosquito absence, and function well in any habitat. Mosquito natural enemies usually affect the larval stages. The diversity of larval habitats, feeding behaviour and physiology probably provides an insurmountable challenge to the development of a single control agent for all mosquito species [82, 83].

Biological control can be broadly categorized into two divisions: natural biological control which is vector reduction caused by naturally occurring biotic agents, and applied biological control which refers to planned human intervention to deliberately add natural enemies to a habitat to reduce vector population (augmentation) or to protect the agents already present (conservation) by manipulating the environment to optimize natural biological control through minimizing detrimental effects on natural enemies or by enhancing their efficacy. Biological control agents are more likely to cause significant mortality in permanent habitats than in ephemeral habitats. However, natural biological control alone does not usually reduce vector populations sufficiently to interrupt disease transmission. Two major types of augmentation are inoculation and inundation. With *inoculative* releases, small numbers of natural enemies are introduced that are expected to reproduce in the environment and provide long-term vector suppression over successive generations. For inundative releases, overwhelming numbers of organisms are released to produce an immediate decline in a vector population. Invertebrate pathogens include viruses, bacteria (*Bacillus thuringiensis israelensis* and *B. sphaericus*), protists (*Nosema algerae*, *Vavraia* spp. and *Amblyospora connecticus*), fungi (*Lagenidium giganteum*, *Coelomomyces* spp., and *Culicinomyces clavisporus*) and nematodes (*Romanomermis culicivorax*). Also, invertebrate predators (*Toxorhynchites* spp. and the copepod *Mesocyclops aspericornis*) and to a lesser extent vertebrates such as larvivorous fish (*Gambusia affinis*, *Poecilia reticulata* and *Aphyocypris chinensis*) have been experimented upon and/or utilized for biological vector control [84]. However, both abiotic (temperature, pH, salinity, organic matter, oxygen levels, toxic agents, habitat type and size and water depth) and biotic (ecology, target species, host specificity and adaptation, dispersal and host-finding abilities, infectivity or capture ability, persistence mechanisms, generation time and population age structure) factors can affect the efficacy and sustainability of biological control, and the suitability of a habitat must be verified at each new location. Biological control has many perceived advantages. It is relatively natural and host specific, it can be self-perpetuating, and it does not adversely affect beneficial invertebrates. As attractive as biological control is in principal, in practice this technique has had limited success in malaria vector control [82, 83].

7. Innovative tools for malaria vector control

Vector suppression plays a pivotal role in the control of mosquito-borne infectious agents. In light of contemporary control constraints, novel approaches are required to achieve effective protection against malaria vectors. Several innovative genetic approaches are being applied to microbial organisms to extend their usefulness as vector control agents. Implementation of IVM requires combinations of control measures that are critical in providing optimal control with minimal detrimental environmental outcomes. With the selection of resistance, new insecticides and novel approaches to vector control are being developed [85]. Innovative approaches invariably being harnessed for contemporary vector control include Durable wall linings, attractive toxic sugar baits, long-lasting topical repellents, spatial repellents, entomopathogenic bacteria traps, fungus-impregnated targets, eave tubes and new molecules for IRS, i.e. chlorfenapyr, including improved housing [42, 86–88].

7.1. Genetic control

Reviews of potential genetic control approaches have invariably included discussion of their operational feasibility against vectors of disease, progress made in population suppression of an increasing number of vectors and population replacement of disease vectors with harmless forms of the same species. Population replacement involves modification of the genetic

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structure of a disease vector in a way that favours human benefit. The desired modification ('useful gene') would be one that prevents disease transmission, either by altering vector behaviour or by producing some physiological change in parasite-vector interaction. The species specificity and non-polluting properties of genetic methods, in contrast to insecticides make the approach attractive. The choice of genetic method for a given species depends on the control strategy to be adopted, whether focal, i.e. adjusted to local needs, or in an area wide rolling programme [89]. The sterile-insect technique (SIT) or sterile-insect release method (SIRM) is the only genetic approach to control that has succeeded on an extensive practical scale with operational effectiveness. SIT is based on the release into the natural habitat of large numbers of the target vector, sterilized in a breeding factory. The released insects carry dominant lethal mutations in their reproductive cells, due to treatment with ionizing radiation or chemical mutagens. All wild female mating with such a male lays sterile eggs. The success of SIT depends on the sterile male's capacity to locate, attract and mate with wild females, in direct competition with wild males. Field trials of SIT against mosquitoes have been conducted on *Culex pipiens quinquefasciatus* in Florida, USA, *An. albimanus* in El Salvador, *An. stephensi* in southern India and *An. arabiensis* in Sudan [89]. The feasibility of integrating sterile-insect technique (SIT), for population reduction of *Ae. albopictus* to prevent and control of chikungunya and dengue, has been considered in the context of IVM in Mauritius [90]. The major technical aspects of mass rearing to be evaluated and improved in mosquitoes are: (1) automated mass rearing, (2) genetic sexing, (3) rapid sterilization, (4) quality control, (5) transportation and release and (6) trapping to evaluate progress [91]. The infection of mosquitoes with *Wolbachia* spp. has been considered to carry a gene for vector competence but would depend on (1) introducing such an 'incompetence' gene into *Wolbachia*, (2) associating *Wolbachia* with *Anopheles* and (3) ensuring that the 'incompetence' gene product, expressed in *Wolbachia*, reaches the gut or salivary glands, which are sites occupied by the malarial parasites [92]. Among all potential methods of genetic control of vectors of disease, SIT has the greatest potential of being effective and economically viable. SIT is at its most effective in combination with other control measures, and it probably extends the effective life of insecticides by slowing down the evolution of resistance [93]. Population replacement remains a distant dream, although research on it provides a rich source of new information on vector physiology and genomics [94, 95].

7.2. Immunological control

Immunological approaches have also been harnessed for the control of malaria vectors. Development of anti-mosquito vaccines reduces blood-feeding and/or pathogen transmission. Their advantages include specificity, safety and cost, ease of administration, long-term protection and absence of residues in the environment. The practicality of vector-blocking vaccines has been given a significant boost by studies that provide protection against pathogen transmission. Advances in immunobiology, genomics, proteomics, DNA immunization and other vaccine-related technologies provide a foundation for new ways to control vectors mosquitoes and malaria [96]. Anti-mosquito vaccines could be designed to disrupt blood feeding, impair reproduction and block development and transmission of mosquito-borne infectious agents. Important resources for anti-mosquito vaccines have been generated from mosquito expressed sequence tags and genome sequencing projects. Attempts have been made to vaccinate against malaria parasites transmitting mosquitoes such as *An. quadrimaculatus* [97], *An. stephensi* [98–100], *Anopheles tessellates* [100, 101], *Anopheles farauti* [102] and multiple *Anopheles* spp. [103, 104].

Most of these contemporary vector control methods have shown to be successful only in small scale- and, more rarely, in large-scale- and country wide programmes. The IVM strategy provides a platform for integrating these into vector control programmes across the malaria-endemic countries in the tropics. However, clear commitment from national authorities including long-term support from funding partners will be required for effective and sustained malaria vector control [105]. Prompted by fragmentary empirical evidence to inform policy formulation for rational vector control, malaria control programmes are encouraged to adopt the WHO-led IVM strategy [49] underpinned by evidence-based decision-making process and a coherent monitoring and evaluation component [13]. The approach should incorporate routine insecticide resistance surveillance and inherent resistance mechanisms to inform decisions and policy changes on insecticide resistance management operations [106].

8. Status of IVM implementation for combating malaria

Integrated vector management has been harnessed for the control of malaria vectors in various endemic countries according to the five key elements of the strategy. In response to the call by the WHO for member states to implement IVM, most VBD-endemic countries have adopted IVM as a pivotal approach to vector control and developed relevant policy documents particularly for malaria vector control. In Mauritius, IVM is one of the three principal components of preventing reintroduction of malaria. The strategy focuses on bi-weekly routine island-wide larviciding with temephos based on entomological surveillance, and indoor and outdoor residual spraying at and around the port and airport with DDT or lambda-cyhalothrin every six months [90]. IVM targets former malaria foci and high-risk areas around migrant workers' residences [107]. Tanzania has been implementing IVM with ITNs, IRS and LSM including environmental management and larviciding using Bti [108, 109]. Notably, IVM has mostly been harnessed for malaria vector control with minimal utilization as an overarching strategy for VBDs. This is exemplified by Kenya [110], Malawi [15], Mozambique [111], Namibia [44], Tanzania [108], Zambia [49], Zimbabwe [112], most of which were pioneers in implementing the approach. The utilization of IVM for multiple VBD control has been compromised by a lack of requisite resources and the inherent cross-sectoral collaboration. It is noteworthy that in some countries such as Swaziland, Botswana, Lesotho, Namibia, Seychelles, Madagascar and South Africa, the presence of VBDs is almost negligible.

With the increasing emergence (dengue, Zika) and re-emergence (chikungunya, yellow fever) of VBDs, countries have embarked on consolidating their IVM policy and strategic documents. In the Comoros, further to the low levels of insecticide resistance observed in the main

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mosquito vectors of the island (*Cx. p. quinquefasciatus*, *An. gambiae*, *Ae. aegypti and Ae. albopictus*), the optimism is high to implement IVM as a more realistic and feasible approach for the control of malaria, bancroftian filariasis, dengue, chikungunya and rift valley fever [113]. Rwanda has developed a comprehensive IVM strategic plan to improve the ecological soundness, cost-effectiveness and sustainability of vector control interventions. The strategy incorporates interventions with clear implementation and collaborative arrangements, strengthened entomological monitoring and surveillance including resistance management [114]. To improve control of VBDs, Uganda has successfully consolidated strategic planning and operational frameworks for VBD disease control and established an evidence-based IVM approach. The country envisions improved VBD control by operationalizing implementation arrangements as outlined in the IVM strategic guidelines [115, 116]. Equally, South Sudan has developed a draft strategic plan for control of VBDs [117] and has embarked on strengthening frameworks for implementation [51]. Eritrea has updated, revised and widened the scope of its IVM strategy due to increasing malaria transmission and challenges in vector control [118]. Ethiopia has developed an IVM strategy and plan of action to include dengue fever and other VBDs; and establishing a coordination mechanism with relevant sectors, including a multi-sectoral task force for capacity building in IVM and surveillance; and to actively engage in advocacy, communication and social mobilization.

IVM strategies have been implemented in Mosquito Control Programmes (MCPs), which aim to reduce the cost and optimize protection of the populations against VBDs in the Americas, and research has been conducted to evaluate MCPs strategies to improve vector control activities [119]. Reviews and case studies have been conducted to discuss and analyse the major strategies currently employed in an effort to minimize the burden of VBDs, and the major progress and achievements resulting from international as well as local efforts [120]. Studies considering how one or more interventions can impact multiple VBDs have been conducted to guide the development of an IVM programme to assist the elimination of malaria and lymphatic filariasis [121]. The contribution of vector management methods has also been critically reviewed to prevent and control outbreaks of West Nile virus infection and to present the challenges for Europe [122]. Expansion of IVM to promote healthy environments has been proposed to control pests, improve cleanliness of communities, increase structural soundness and decrease health disparities that arise from external hazards [123].

9. Challenges and opportunities for establishing viable IVM strategies

While the expectation to reduce the burden of VBDs in endemic countries is high, the operational challenges to effective vector control are enormous. Integrated management of malaria vectors still remains an underdeveloped component of malaria control policies in most programmes. This could in part be attributed to the shortage of health workers in general, but other key contributors are technical, operational, political and social economic in nature. Major challenges to malaria control include very high malaria transmission intensity, low coverage of proven malaria control interventions, inadequate health care resources, a weak health system, inadequate understanding of malaria epidemiology, the impact of control interventions and insecticide resistance development in mosquito vectors. The key challenges are categorized and elaborated further as outlined below:

Limited ability to fully utilize the available tools: In most programmes, vector control is managed by naïve, low calibre and mediocre level public health workers devoid of field experience or is hijacked by clinicians, who are mostly less competent in entomology and vector control. Such programme managers are not receptive to well-informed expert technical advice and are naïve to fully participate in the discourse on vector control and are not open to innovative ideas. The competent public health entomologist and vector control specialists are by and large left frustrated. While surveillance monitoring and evaluation, and operational research are key components of malaria control strategies, activities in the area of vector control are always less prioritized as clinically inclined managers tend to have a predilection for drug efficacy studies. The lack of skills and knowledge has resulted in apathy and unreceptiveness towards scientific results generated by field teams, poor utilization of available tools, low up take of available innovative vectors control tools, vector surveillance, and resistance monitoring and management guidance. While non-governmental organizations (NGOs) play a key role in complementing public sector endeavours in health service delivery, in post-conflict environments, most NGOs have engaged vector control people with minimal or no field experience to effectively transfer competences to the local cadre. Consequently, the IVM strategy has not been fully harnessed for strengthening vector control. However, this trend should be guarded against if meaningful gains are to be attained from contemporary vector control efforts.

Lack or minimal inter-sectoral collaboration amongst stakeholders: Across-sector collaboration amongst stakeholders-public and private sectors—including community empowerment, involvement and participation—and integration amongst VBDs remains an obvert constraint to effective vector control. Even in situations where various partners exist and are working on VBDs control, coordination remains negligible. The situation is aggravated in emergency situations, particularly by the notable absence of entomologists at central level to adequately coordinate entomological resources. There are nominal levels of utilization of available guidance from the WHO and other collaborating stakeholders, as well as limited sharing of experiences by programmes. In recent years, cross-border collaboration and inter-sectoral collaboration on VBDs have been inefficient relative to collaboration on other diseases such as polio elimination [124].

Minimal or absent operational research competences: Efforts to revamp insectaria and entomology laboratories have been embarked upon by various funding organizations. However, entomological infrastructures in most countries are either lying in a state of dilapidation or operating at sub-optimal scale to be useful in any way. They lack requisite equipment and commodities, including a minimal number of dedicated personnel. In certain cases, central laboratories do exist with adequate numbers of staff but lack field laboratory at regional or local levels, making data collection inefficient and thus eroding the potential of existing entomological competencies. There is minimal evidence-based decision-making to provide technical guidance to policy makers and programme managers. Limited operational research and country-wide spatio-temporal mapping of VBDs are also amongst the major challenges. The situation is aggravated by inadequate in-country information systems, lack of geo-coding of relevant attributes and centralized data bases for easy information retrieval as and when it is required.

Emergency situations, environmental and climate changes: In conflict and post-conflict environments, security is the major impediment to successful vector control. There is lack of technical and physical infrastructure and personnel are mostly of mediocre caliber. The situation is compounded by high personnel turn over and a lack of touch with the latest information. While these settings experience human resource crises and competent skills are scarce, flexible people who are not possessive about 'the way things are done around here' are needed. Most vector control issues are left in the hands of non-professionals who tend not to be open to constructive criticism. Appropriate requisite regulatory and legislative framework for public health is also non-existent. Equally, the changing climate and land use patterns are having a toll on the efficacy of the once effective vector control interventions. This necessitates innovation and implementation of local situation amenable interventions.

Community sensitization, mobilization and information sharing: There is inadequate and inconsistent social mobilization and community sensitization and insufficient participation and ownership resulting in low compliance with existing interventions. Mass media and interpersonal communication channels have been used to disseminate advocacy, behavioural change and information and education communications to enhance community participation. Unfortunately, such communications never run consistently annually due to limited resources for requisite activities and are hampered by issues of socio-economic and political factors, cultural aspects and alleged abuse of vector control interventions. There is minimal innovative ways to engage the communities in vector control activities including entomological surveillance and resistance monitoring, including information on country and multi-country level experiences with IVM and IRM. Documentation and sharing of lessons learnt from the field will be essential and will to some extent offset the dependency on the overstretched international technical assistance. However, this requires availability of local competences for documenting the experiences.

Funding and operational constraints: Vector control is mostly donor driven, but the funding is often restricted and with prescribed activities. This tends to have detrimental effects on the ambitious and innovative programme officers who may want to adapt the interventions to the local situation. Most development partners have neglected health system strengthening. Therefore, collaborative approaches and strong political commitment and consistent financial support are required to scale up cost-effective interventions for vector control, including focused research and inter-country cooperation and exchange to share best practices. Effective deployment of vector control interventions including entomological monitoring is hinged on efficient operational logistics including transport systems. Programmes in most settings do not have transport dedicated to entomology and vector control but do have pool vehicles, which in most cases are not easy to access as transport officers often lack an understanding of vector control.

10. Recommendations for moving forward

Notably, tackling contemporary vector control challenges will require strategic efforts beyond those aimed at addressing the human resources crisis. Opportunities for strengthening vector control exist and could be harnessed for effective VBD control. Looking forward; the following are proposed priority actions for advancing IVM implementation within the context of its five key strategic elements and the inherent effective monitoring and evaluation in line with the WHO recommendations:

Development of IVM policy frameworks: To improve national vector-borne disease control programmes, countries should develop national IVM policy and national policy on pesticide management. Development of relevant strategic documents and improving the uptake and use of policy documents produced by the WHO will be critical to achieving this end [8]. Particularly in emergency situations that should include the provision of guidance on IVM in humanitarian emergencies.

Institutional arrangements and Inter-sectoral collaboration: Successful inter-country and inter-sectoral collaborations and vector control initiatives are needed to achieve effective control. However, this will require establishing national steering committees on IVM and national coordinating units on vector control, together with developing and field testing approaches for engaging community organizations in an effective partnership with the operational and regulatory personnel of health and local government departments to improve implementation. Although engagement of sectors other than health is important for vector control, the success of inter-sectoral collaboration will be determined by the extent to which other sectors impact vector proliferation [124].

Vector surveillance and insecticide resistance monitoring: Effective IVM strategies need improved entomological surveillance, risk assessment, preparedness and response; including plans for IRM. Therefore, planning and implementation will require the epidemiological surveillance system on vector-borne diseases, and setting up sentinel sites for vector surveillance and insecticide resistance monitoring. In this regard, countries should (1) develop, evaluate, and promote the effective use of vector control methods, in the context of IVM; (2) support improvements in surveillance, including the collection and use of case reports, environmental and demographic data, and other information to better understand disease distribution patterns and strengthen disease control programmes [125].

Operational research agenda on vector-borne disease control: Planning and implementation will require operational research priorities and expected outcomes on vector control to be used in deployment of programmes. In areas prone to malaria epidemics, understanding the local distribution of the disease and its relation to environmental and demographic factors will help public health officials improve the prevention and control activities they direct. The role of operational research and the interactions between research institutions, vector control programmes, civil society organizations, and of financial and technical partners to address challenges and to accelerate translation of research into policies and programmes should be considered [14]. Therefore, strengthening the capacity of vector control programmes to conduct operational research, publish its findings and improving linkages between them and research institutes may aid progress towards effective control [126].

Standard operating procedures or protocols need to be developed for entomology teams to collect specimens and map their locations, including insecticide susceptibility status. For the purposes of mapping the presence or absence of a vector, a much more targeted and streamlined sampling strategy with optimal collection methods, e.g. animal-baited traps, light traps, should be determined. Programmes need to plan operational, or implementation research activities for increasing effectiveness of current vector control tools and to better engage specific groups such as the military, mobile and migrant workers and marginalized populations to improve access and appropriated interventions.

Community sensitization, mobilization and information sharing: Advocacy communication and social mobilization would be important in putting national strategic and implementation plans on IVM in place. There should be consistent community sensitization via mass media and interpersonal communication channels to disseminate advocacy, behavioural change and information and education communications and address issues of socio-economic-political factors, cultural aspects, urbanization or climate and abuse of vector control tools and enhance community participation. The key messages, based on scientific evidence and information available and disseminated without delay, are crucial for an effective and urgent response [14]. Campaigns on behavioural change and community mobilization on vector control should be conducted. Lessons learned from programmes will provide the requisite platform for accelerated implementation of IVM.

Capacity building: Developing greater capacity in vector control programmes for collecting, managing and analysing malaria case reports and environmental data is useful for planning control operations. Professional training and experience in entomology and vector control are critical for running an IVM programme that makes appropriate use of all available control methods. Certified training courses on IVM and judicious use of pesticides should be in place at national or regional level. Organization and management of IVM requires standards for professions and careers in vector control and public health entomology to be established [127]. Organizing and implementing regional training programmes, professional associations and technical assistance networks that can operate over the long term to build and sustain the human resource capacity needed for effective vector control programmes. Making headways would require enhancing national vector control capacities in terms of human and infrastructural resources to enable efficient monitoring and management of malaria vectors [128]. Governments in malaria-endemic countries should mobilize enough local resources to supplement the limited and restricted donor funding. As efforts are made towards addressing inherent limitations, seeking rare and often overstretched external technical assistance by control programmes will be critical. This will necessitate institution of local training programmes.

11. Discussion

Most malaria-endemic countries have adopted and implemented the IVM strategy. Although the approach has primarily been harnessed for malaria control, countries are presently consolidating their strategic plans and operational frameworks to incorporate other VBDs in the IVM approach. Efforts are being expended towards establishing requisite infrastructure and human resources for vector control. However, control programmes are still faced with several limitations. Successful IVM would require circumventing contemporary challenges to ensure universal access to interventions.

Effective vector control demands for diligent entomological capacity and necessitate adequate requisite financial and human resources and pertinent physical infrastructural strengthening at national and local levels [7]. The major limitations for capacity-building for IVM are lack of essential physical infrastructure (insectaries, laboratories and equipment), financial resources and technical resources (qualified vector control human resources-medical entomologists and vector control specialists) to support entomological monitoring and evaluation of vector control interventions and to manage and implement IVM. The technical assistance provided by the very few resources that exist is extremely strained. Addressing deficiencies in all these areas of public health capacity would be necessary for the successful implementation of IVM. This would need strengthened collaboration with stake holders including local and international academic and scientific institutions and line ministries such as environment and agriculture.

An IVM-based process should be cost-effective, guided by operational research and subject to routine monitoring and evaluation of impact on vector populations and disease transmission [13]. Evidence-based vector control requires regular collection of comprehensive entomological data from spatially segregated geo-locations to adequately inform decision-making on effective targeting, deployment and monitoring of interventions. Monitoring by countries should incorporate key elements of entomological surveillance, including determining species composition, establishing vector distribution and seasonality, collecting vector behaviour data, conducting insecticide susceptibility testing and establishing underlying mechanisms of resistance. Mosquito vectors have developed insecticide resistance to all four classes of public health insecticides, which are spreading with great potential to compromise vector control efforts [70]. Research on innovative vector control tools should be enhanced to provide adequate convincing evidence that can compel and foster donor flexibility. This will be critical in light of selection of insecticide resistance and outdoor/residual transmission. Otherwise vector control will remain dependent on the archaic tool box full of ineffective interventions. Countries should improve global insecticide resistance tracking and get support for developing management plans and the development of an online interactive platform for mapping level resistance [129].

The WHO recommends IVM as a pivotal platform for combating vector-borne diseases. To this effect, several policy and strategic documents as well as training materials have been developed, including a Global Strategic Framework that sets out the principles and approaches to IVM. For effective vector control, endemic countries need to develop three key documents: (1)

an IVM-based vector control strategy; (2) a resistance monitoring and management plan; and (3) vector surveillance guidelines, according to WHO recommendations. There is significant opportunity to integrate vector control for VBDs because in many areas either the same vectors transmit more than one disease, or the local vectors share common ecology. Therefore, IVM should focus on redesigning programmes in the context of vector surveillance, insecticide resistance response, environmental and climate change, cross-border initiatives and IVM in emergency situations [129]. The WHO Emergency Response Framework also stresses the need of sufficient risk reduction and preparedness capacities in member states; and institutional readiness of WHO in ensuring that adapted disease surveillance, early warning and response systems are in place. Risk assessments for yellow fever, chikungunya, dengue and Zika should be prioritized in all settings with the presence of *Aedes* spp. mosquitoes.

Successful implementation of IVM requires adequate financial, human and technical resources, a robust entomological monitoring and resistance surveillance and management system, and demands for meticulous operational considerations and preparedness: strengthened operational research to generate data for decision-making and evaluation of new vector control tools; establishing pertinent physical infrastructure-sentinel sites and laboratory and insectary facilities; adherence to WHOPES specifications and WHO recommendations for procurement; institutionalize data repositories and capacity to implement the interventions. Countries should develop strategic and operational frameworks and maximize impact of current tools. This necessitates adequate planning including detailed situation analyses to obtain relevant local data and implementation frameworks (adherence to pertinent regulatory obligations for registration of insecticides, developing overall multi-year budgets for operations). It will need strengthened collaborations with all stakeholders with vested interest in vector control and insecticide resistance including the funders.

12. Conclusion

Despite the slow pace, malaria-endemic counties are embracing and consolidating the IVM approach. The development and implementation of IVM with strict adherence to the five key elements of the approach are crucial for effective operational malaria vector control. Regular need assessments for vector control human and infrastructural resources and technical support to facilitate capacity building in entomological surveillance and monitoring for evidence-based decision-making in vector control are critical for successful IVM, including guiding development of IVM strategic plans, country IRM plans and vector surveillance plans, advocacy for the global plan for IRM (GPIRM), guidance on IVM in humanitarian emergencies, and supporting entomological surveillance, risk assessment, preparedness and response. Effective IVM necessitates strengthening of research, studies of the efficacy and cost-effectiveness of IVM, knowledge, attitude and practice, community participation, and development and harmonization of BCC/IEC messages and effective delivery of materials. Insecticide resistance requires an emergence approach and IVM in humanitarian emergencies need appropriate guidance. The IVM approach can be harnessed as a platform for strategic planning and deployment of vector surveillance, resistance monitoring and management. Thus, rational

IVM strategies should be a pivotal platform for malaria vector control in endemic countries, particularly in conflict and post-conflict or emergency situations. Countries should develop policies, standard operational procedures, country specific guidelines; strengthen human resource capacity, inter-sectoral collaborations, advocacy, legislation and regulation, including community sensitization and engagement. However, significant coordinated response amongst stakeholders and political commitment is needed for timely and effective policy implementation within the context of a national health system. This will require a realization that IVM will yield a positive return for investment in terms of reduced disease burden and the resulting social and economic gains.

Conflict of interests

The author declares that there is no conflict of interests regarding the publication of this manuscript.

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