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Challenges and Strategies of Mosquito Control in Sudan

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Abstract

Mosquito-borne diseases constitute a persistent public health challenge in tropical and subtropical regions worldwide. This paper provides a comprehensive overview of mosquito control strategies relevant to Sudan. The proliferation and diverse types of mosquitoes in Sudan are driven by environmental, climatic, and infrastructure-related factors. The failure of mosquito control efforts in Sudan is largely attributable to the combined effects of conflict, deteriorating public health infrastructure, and severe shortages of operational resources. Interconnected factors, such as environmental and climatic pressures, infrastructure deterioration, conflict and population displacement, inadequate human and logistical resources, insufficient surveillance, waste accumulation, and increasing challenges related to insecticide resistance and vector adaptation and vector adaptation. Personal and household protection constitutes an important component of mosquito control, particularly in areas where mosquito-borne diseases are endemic. Personal measures such as repellents, protective clothing, and insecticide-treated bed nets can reduce direct human-mosquito contact, while household measures such as source reduction, improved drainage, waste management, physical barriers, and mosquito traps can reduce mosquito abundance and access to human hosts. Environmental source reduction should remain the foundation, supported by targeted biological and chemical control and, where feasible, carefully evaluated novel technologies. Sustained surveillance, intersectoral coordination, and community participation are essential for achieving effective, environmentally responsible, and durable mosquito suppression.

Keywords

Mosquito Control, Sudan, Challenges, Strategies, Personal Protection, Household Protection

1. Introduction

Mosquitoes, long recognized as major vectors of disease, have exerted a profound impact on human health, economic stability, and ecological systems throughout history. The complex and dynamic interactions between humans and mosquitoes underscore the persistent global challenge posed by mosquito-borne diseases. Despite substantial scientific advances in medical entomology and public health, these diseases remain widespread, emphasizing the ongoing need for sustained research, prevention, and effective control strategies. Mosquito-borne diseases constitute a persistent and escalating public health challenge in tropical and subtropical regions worldwide [1]. Mosquitoes are among the most medically significant arthropods worldwide due to their role as biological vectors of a wide range of pathogens affecting both humans and animals [2]. Through blood-feeding, female mosquitoes transmit viruses, parasites, and helminths responsible for some of the most prevalent and severe infectious diseases globally. Notably, mosquitoes themselves are generally unaffected by these pathogens, having evolved physiological mechanisms that allow them to tolerate, suppress, or limit infection [3]. Currently, five invasive *Aedes* mosquito species are known to be established in Europe, namely *Aedes albopictus*, *Aedes aegypti*, *Aedes japonicus*, *Aedes atropalpus*, and *Aedes koreicus*. Among these, *Aedes albopictus* and *Aedes aegypti* have been incriminated as the primary vectors responsible for recent outbreaks of chikungunya and dengue fever in Europe. Experimental studies and field observations further suggest that these invasive species possess the capacity to transmit additional pathogens of significant public health concern [4]. Mosquitoes transmit a wide range of medically important pathogens, including viruses, bacteria, protozoa, and nematodes, which cause serious diseases such as dengue fever, yellow fever, Zika virus disease, chikungunya, West Nile fever, malaria, and lymphatic filariasis [5]. Collectively, these diseases impose a substantial burden on global public health systems. Malaria alone accounts for hundreds of millions of infections annually and remains a leading cause of mortality in many low-income regions. Dengue fever, meanwhile, has emerged as one of the fastest-growing vector-borne diseases worldwide, with recurrent outbreaks across tropical and subtropical regions [6]. Beyond their direct health effects, mosquito-borne diseases exert profound socio-economic consequences, including reduced productivity, increased healthcare expenditures, and disproportionate impacts on displaced and marginalized populations [7].

In Sudan, the medical and public health importance of mosquitoes has intensified in recent years due to the convergence of environmental, climatic, and humanitarian factors [8]. Limited capacity within the health system—particularly in the diagnosis of infectious diseases—has resulted in the frequent misclassification of febrile illnesses, with many conditions incorrectly diagnosed as malaria or other similar febrile diseases. This diagnostic challenge not only leads to an overestimation of malaria cases but also contributes to a significant underestimation of arboviral diseases and their associated socio-economic impacts. Furthermore, defi-

ciencies in public health infrastructure, water supply systems, waste management, and vector control programs—especially in urban centers such as Khartoum—have created favorable conditions for mosquito proliferation, including widespread stagnant water, debris accumulation, and unregulated household water storage [9]. The situation in Sudan illustrates how mosquito-borne diseases serve as indicators of broader public health system fragility. The interaction between vector ecology, environmental degradation, population displacement, and weakened health services underscores the urgent need for sustainable and integrated mosquito control strategies [10]. Addressing the medical and public health importance of mosquitoes in Sudan therefore requires not only entomological interventions, but also strengthened disease surveillance, improved environmental management, and enhanced health system resilience [11].

This paper provides a comprehensive overview of challenges and strategies of mosquito control in Sudan, with particular emphasis on the current environmental and humanitarian context.

2. Methods

This article was prepared as a narrative review informed by a structured search of PubMed/MEDLINE, Google Scholar, and relevant reports and technical resources from the World Health Organization and Sudanese public-health authorities. Searches used combinations of the terms "Sudan", "mosquito control", "Anopheles stephensi", "Anopheles arabiensis", "insecticide resistance", "vector surveillance", "malaria", "dengue", and "integrated vector management". Publications and reports were considered when they addressed mosquito ecology, vector distribution, insecticide susceptibility, disease prevention, or control strategies relevant to Sudan; studies from neighboring countries and the wider region were used only to provide context where Sudan-specific evidence was not available.

3. Results

3.1. Biology and Life Cycle of Mosquitoes

Mosquitoes are holometabolous insects belonging to the order Diptera, characterized by complete metamorphosis and remarkable ecological adaptability [12]. Their success as vectors of human and animal pathogens is closely linked to their complex life cycle, physiological specialization, and ability to exploit a wide range of aquatic and terrestrial habitats [13]. Consequently, a thorough understanding of mosquito biology and life history is fundamental to the development and implementation of effective vector control strategies, particularly in endemic regions such as Sudan. The mosquito life cycle consists of four distinct developmental stages—egg, larva, pupa, and adult—each possessing unique morphological characteristics and specific environmental requirements. Oviposition is strictly dependent on the availability of water, making aquatic habitats a critical determinant of mosquito population dynamics [14]. Female mosquitoes lay eggs either directly on water surfaces, along water margins, or in environments that become tempo-

rarily flooded. Under favorable conditions, a single female may produce multiple batches of eggs during her lifetime, thereby accelerating population expansion [12]. Egg morphology and oviposition behavior vary considerably among mosquito genera. Anopheles species deposit elongated eggs individually on water surfaces, each equipped with lateral floats that enhance buoyancy [15]. In contrast, Culex species lay adhesive eggs arranged in characteristic raft-like structures, often comprising several hundred eggs. Aedes species display a distinctive ecological adaptation by laying eggs singly in dry or semi-dry containers, where the eggs can remain viable for prolonged periods until contact with water induces hatching. These reproductive strategies enable mosquitoes to withstand environmental fluctuations, including droughts and intermittent control efforts [16]. Following hatching, mosquito larvae undergo four aquatic instars (I-IV), during which they actively feed and grow. Larvae rely on atmospheric oxygen and employ species-specific respiratory mechanisms [17]. Anopheles larvae respire directly at the water surface through spiracles, whereas Culex and Aedes larvae use a siphon to access air. Certain genera, such as Mansonia, exhibit specialized adaptations that allow larvae to obtain oxygen by piercing the roots of aquatic plants. Larval feeding involves filtering microorganisms and organic debris from the water using brush-like mouthparts, rendering larval habitats particularly sensitive to water quality and nutrient availability [18]. The pupal stage represents a transitional yet critical phase in mosquito development. Although pupae are non-feeding, they are highly mobile and responsive to environmental stimuli [19]. After an aquatic developmental period that typically spans approximately one week from egg to pupa, adult mosquitoes emerge and transition to a terrestrial and aerial existence. Newly emerged adults initially rely on plant-derived sugars, such as nectar, to meet their metabolic energy requirements [19]. Sexual dimorphism in feeding behavior is central to mosquito-borne disease transmission. Male mosquitoes feed exclusively on plant sugars, whereas females require a blood meal to obtain the proteins necessary for egg maturation following mating. Host preference varies widely among mosquito species and may include humans, domestic and wild mammals, birds, reptiles, amphibians, and occasionally invertebrates. This broad host range enhances mosquito vectorial capacity and facilitates the transmission of diverse pathogens [12] [20]. Mosquito breeding habitats are highly heterogeneous and include stagnant water bodies, uncovered water storage containers, construction-related water accumulations, agricultural fields, and natural phytotelmata such as tree holes and pitcher plants. The diversity of breeding sites, coupled with rapid developmental cycles and high reproductive potential, explains the persistence and proliferation of mosquito populations in both urban and rural environments [2] [21]. In Sudan, where climatic variability, seasonal rainfall, and rapid urban expansion intersect, the biological characteristics and ecological adaptability of mosquitoes pose substantial challenges to control efforts. A comprehensive understanding of mosquito life history, breeding ecology, and environmental responsiveness is therefore essential for the design and implementation

of integrated vector management strategies tailored to local ecological and socio-economic conditions [22].

3.2. Proliferation of Mosquitoes in Sudan

In recent years, Sudan has experienced a notable rise in mosquito-borne disease outbreaks, driven by climatic variability, rapid urbanization, environmental degradation, and prolonged humanitarian crises in addition to the impact of the conflict/war [23]. The proliferation and diverse types of mosquitoes in Sudan are driven by environmental, climatic, and infrastructure-related factors. Recent climatic trends in Sudan, characterized by rising temperatures and increasingly intense rainfall events, have created favorable ecological conditions for mosquito proliferation [24]. Seasonal rains and flooding often produce extensive areas of stagnant water in streets, residential neighborhoods, and other low-lying areas, providing suitable breeding habitats for *Anopheles* and *Aedes* mosquitoes. At the same time, disruptions to water supply systems, particularly following damage to water networks and electricity infrastructure, have forced many households to store water in uncovered containers and barrels, creating additional breeding sites for *Aedes* mosquitoes and increasing the risk of dengue transmission. Climate-related changes may also accelerate mosquito development and expand the duration and geographic range of suitable breeding conditions. In residential areas, the accumulation of vegetation, including weeds and small trees, may further increase the availability of shaded and humid environments favorable to mosquito survival. These conditions can affect not only residential communities but also workers in sectors such as agriculture and construction who may be exposed to mosquito-infested environments during their daily activities [25]. The combined effects of heavy rainfall, flooding, rising temperatures, inadequate water storage practices, and environmental degradation have contributed to increased mosquito abundance and the emergence of mosquito-borne disease outbreaks, including recurrent dengue outbreaks, particularly in Khartoum State. These local trends are consistent with the broader global increase in dengue incidence and its geographic expansion. In Sudan, however, limited disease surveillance capacity and constrained public health response mechanisms may further increase vulnerability to outbreaks [24] [26].

The deterioration of infrastructure and humanitarian conditions can significantly contribute to the proliferation of mosquitoes in Sudan [27]. Blocked or poorly maintained urban drainage systems, together with the accumulation of solid waste, can create persistent water-holding environments that provide suitable breeding sites for mosquitoes, particularly in the absence of regular public health interventions. In addition, ongoing conflict and the weakening of the healthcare and public health systems have disrupted routine mosquito-control activities, including insecticide spraying campaigns. Shortages of pest-control supplies and interruptions in entomological surveillance further limit the capacity to monitor mosquito populations and respond effectively to emerging outbreaks.

Collectively, these infrastructure and humanitarian challenges can increase mosquito breeding opportunities and undermine the implementation of sustainable mosquito-control programs [28].

3.3. Ineffectiveness of Mosquito Control in Sudan

The emergence and spread of the invasive malaria vector Anopheles stephensi represent an additional challenge for Sudan. Published surveillance has documented this species in eastern Sudan, including Port Sudan and Tokar in Red Sea State and Abu Alnaja in Gedaref State, with subsequent reports confirming its wider distribution across multiple states, including Khartoum, Gezira, Sennar, River Nile, Northern, North Kordofan, and South Darfur [27] [29]. Its presence warrants expanded species-specific surveillance and evaluation of its susceptibility to locally used insecticides. However, the Sudanese insecticide-resistance evidence mainly concerns primarily Anopheles arabiensis. Studies of Anopheles arabiensis have documented resistance to pyrethroids (including deltamethrin and permethrin) and DDT in several settings, including Gezira and New Halfa in Kassala State; resistance to malathion, an organophosphate, has also been reported historically in Sudan. In contrast, bendiocarb (a carbamate) susceptibility was retained in the 2011-2014 multi-site study [30]-[32]. These findings demonstrate the importance of insecticide-resistance monitoring in Sudan, but they should not be interpreted as evidence that Anopheles stephensi itself is resistant to these insecticide classes in Sudan.

Overall, the ineffectiveness of mosquito-control programs in Sudan reflects the interaction of several interconnected factors. These include environmental and climatic pressures, infrastructure deterioration, conflict and population displacement, inadequate human and logistical resources, insufficient surveillance, waste accumulation, and increasing challenges related to insecticide resistance and vector adaptation. Addressing these constraints requires sustained investment in public health infrastructure, restoration of vector-surveillance systems, adequate provision of control supplies and trained personnel, improved waste and water management, and the implementation of integrated and context-specific mosquito-control strategies.

4. Discussion

4.1. Personal and Household Protection against Mosquitoes

Personal and household protection constitutes an important component of mosquito control, particularly in areas where mosquito-borne diseases are endemic (**Table 1**). Personal protection measures primarily aim to reduce human-mosquito contact and consequently minimize the risk of mosquito bites and disease transmission. These measures include the use of topical insect repellents, protective clothing, insecticide-treated clothing, insecticide-treated bed nets, and reduction of outdoor exposure during periods of high mosquito activity. Topical repellents are widely used to reduce mosquito-human contact, while protective clothing

Table 1. Methods and strategies of mosquito control in Sudan.

Protection type	Suggestive method	References
Personal protection	Insect repellents (smoke, natural oils)	[33] [39] [40]
	Protective clothing	[34] [35]
	Insecticide-treated bed nets	[37]
	Timing and outdoor exposure	[36]
	Treatment and medication	[53] [38]
Household Protection	Elimination of breeding sites and standing water	[46] [44]
	Barriers and indoor measures (screens on windows and doors)	[54] [49]
	Fans and air movement	[23]
	Waste and household cleanliness	[47]
	Natural mosquito repellents	[41]-[43]
	Proper household waste control	[48]
	Improve drainage and fill depressions and low-lying areas	[45]
	Use household traps	[51]
General strategies	Environmental Management and Larval Source Reduction	[55]
	Chemical control	[56] [57]
	Biological methods	[58]-[64]
	Physical and mechanical area-wide Control	[65] [66]
	Genetic and novel vector-control technologies	[67] [68]
	Integrated mosquito management	[69]

can provide an additional physical barrier against mosquito bites. Clothing that is long, loose, and light-colored can reduce the amount of exposed skin, and permethrin-treated clothing may provide additional protection against mosquito bites [33]-[35].

The timing and duration of outdoor exposure are also important determinants of mosquito-bite risk. Reducing outdoor activities during periods of peak mosquito activity can decrease exposure, particularly in areas where important disease vectors are most active during the evening and nighttime [36]. Insecticide-treated bed nets represent another important personal protection measure, especially in malaria-endemic settings, because they provide both a physical barrier and, when appropriately treated, an insecticidal effect against mosquitoes attempting to feed on sleeping individuals [37]. For individuals travelling to or living in malaria-risk areas, personal protection should be complemented by appropriate medical advice regarding antimalarial chemoprophylaxis, including selection of the appropriate drug, dosage, timing, and duration of treatment [38]. Several additional ap-

proaches have been investigated as supplementary methods of personal protection. Smoke produced by burning selected plant materials has traditionally been used to reduce mosquito activity around people, although its effectiveness may vary according to mosquito species and the source of the smoke [39]. Similarly, natural plant-derived oils have been investigated for their repellent properties, including citronella, tea tree oil, geraniol, neem oil, soybean oil, and other botanical products. However, their efficacy and duration of protection may vary considerably, and therefore they should be considered complementary rather than universally equivalent alternatives to well-established repellents [40]-[43]. Appropriate precautions are also necessary when using concentrated essential oils because skin irritation or other adverse reactions may occur. Household protection complements personal protection by reducing mosquito entry, survival, and breeding around human dwellings. One of the most important environmental measures is the elimination of mosquito breeding sites through the removal of standing water from containers and other water-holding structures around the home. Improving drainage and filling depressions or low-lying areas where water can accumulate can further reduce the availability of larval habitats [44]-[46]. Proper disposal of household waste and debris is also important because discarded containers and other materials can collect rainwater and create suitable breeding sites [47] [48]. Physical barriers can further reduce mosquito entry into houses. Installing and maintaining screens on windows and doors can limit mosquito access to indoor spaces and provide a relatively simple household protection measure [49]. Indoor environmental modifications, including the use of fans and air movement, may also reduce mosquito landing and biting by interfering with mosquito flight and host-seeking behavior [50]. Household mosquito traps have additionally been investigated as a supplementary method for reducing adult mosquito populations within or around residential environments [51]. Effective mosquito control therefore requires a multifaceted and integrated approach that combines environmental, physical, biological, chemical, and modern genetic strategies tailored to local ecological and socio-economic conditions [52].

4.2. General Mosquito Control Strategies in Sudan

4.2.1. Environmental Management and Larval Source Reduction

Environmental management and larval source reduction are important components of integrated mosquito management, but their priority and expected contribution should be determined by the vector species, disease transmission pattern, and local ecology [55] [70].

In Sudan, measures may include improving drainage, clearing blocked drains and irrigation channels, managing waste, and reducing water-holding sites. The emphasis should differ by setting: management of productive larval habitats is particularly relevant for container-breeding Aedes mosquitoes, whereas malaria prevention also requires effective protection against adult Anopheles mosquitoes through appropriate core vector-control interventions.

Area-wide source reduction should focus on sites that cannot be managed effectively by individual households, including public drains, roadside ditches, construction areas, discarded tires and containers, stagnant pools, poorly drained lowlands, and irrigation-associated habitats. Regular mapping and prioritization of productive breeding sites can improve the efficiency of control operations.

4.2.2. Chemical Control

Chemical control remains important when rapid suppression of mosquito populations is required, particularly during outbreaks. Larvicides can be applied to suitable aquatic habitats to prevent adult emergence, whereas adulticides can be delivered through targeted space spraying, ultra-low-volume (ULV) applications, fogging, or indoor residual spraying (IRS) where appropriate [56] [57].

In Sudan, insecticide choice should be guided by current local susceptibility data and should not assume that resistance patterns documented in Anopheles arabiensis also apply to Anopheles stephensi. Species-specific bioassays are particularly important as the distribution of Anopheles stephensi expands.

For area-wide operations, insecticide use should be targeted to surveillance-defined hotspots and the behavior of the target vector. Thermal fogging is not inherently restricted to enclosed settings: it can be used for outdoor space spraying during outbreaks or when rapid suppression of flying adult mosquitoes is required, provided that the insecticide formulation and equipment are approved for that use and weather conditions support effective droplet contact. Applications should coincide with vector activity—typically after dusk or before dawn for Anopheles mosquitoes, and early morning or early evening for day-biting Aedes vectors. Portable indoor space spraying may be appropriate where the target species rests or bites indoors, or where outdoor fog does not adequately penetrate buildings; it should not be treated as a general preference for enclosed environments. Space spraying has little or no residual effect and should supplement, not replace, larval-source management and other locally appropriate control measures. Trained applicators should follow product-label and equipment instructions, use the required personal protective equipment, notify and keep people and animals away from the treatment area as directed, protect food, drinking water and exposed utensils, observe ventilation and re-entry requirements for indoor treatments, and prevent drift toward bystanders, water bodies and non-target habitats. For thermal fogging, the formulation and carrier must be suitable for the equipment, with particular attention to fire and inhalation hazards. Treatment timing and location should be based on surveillance and target-vector behavior, with post-treatment monitoring to assess effectiveness [71] [72].

4.2.3. Biological Control

Biological control uses predators or pathogens to suppress mosquito populations while reducing reliance on conventional insecticides [58]. Larvivorous fish, including Gambusia and Poecilia species, can reduce larvae in suitable aquatic habitats, although their introduction requires ecological assessment to avoid adverse

effects on native fauna [59]. Other larval predators include copepods, dragonfly larvae, water bugs, and predatory mosquitoes such as Toxorhynchites [60].

Microbial control agents, particularly Bacillus thuringiensis, are widely used because of their specificity to mosquito larvae and comparatively low toxicity to non-target organisms [61]. Entomopathogenic fungi also represent a promise ng complementary option, particularly for adult mosquitoes, while botanical larvicides and other plant-derived products may provide additional environmentally oriented tools [62] [63]. However, botanical and microbial approaches require local field evaluation and operational standardization before large-scale implementation.

4.2.4. Physical and Mechanical Area-Wide Control

At the public and area-wide level, physical and mechanical measures can reduce mosquito populations without depending entirely on insecticides. These include community-scale trapping systems, light- or carbon-dioxide-based traps, sticky traps, and other surveillance or suppression devices deployed in targeted locations [66]. Environmental modifications should be linked to locally confirmed breeding habitats rather than assumed to have uniform effects. For example, a community-based intervention that modified water-retaining storm drains in Salvador, Brazil, reduced standing water and immature Aedes mosquitoes, although larger controlled evaluations were recommended before wider extrapolation [73]. Housing interventions involving ventilation also require careful interpretation. An experimental study in rural Gambia found that a ceiling fan reduced Anopheles house entry, whereas a solar chimney did not [50]. Thus, drainage improvements and ventilation may be useful in specific settings, but their expected contribution depends on infrastructure, vector ecology, and local evaluation [45] [49].

4.2.5. Genetic and Novel Vector-Control Technologies

Biotechnological approaches provide potential long-term options for mosquito population suppression or disease-vector modification. These include the Sterile Insect Technique (SIT), Incompatible Insect Technique (IIT), genetically modified mosquitoes with self-limiting traits, and sex-ratio distortion technologies [67]. Their objective is to reduce population density, reproductive capacity, or vectorial capacity over successive generations.

Although such technologies are promising, their application in Sudan would require ecological suitability assessments, regulatory oversight, public engagement, operational capacity, and rigorous risk evaluation. Large-scale field studies and long-term monitoring are necessary before routine deployment [68].

4.3. Integrated Mosquito Management

Integrated mosquito management (IMM) provides a framework for selecting interventions according to local mosquito ecology, disease patterns, surveillance findings, insecticide susceptibility, and available resources [69] [70] (**Table 1**). For malaria, insecticide-treated nets (ITNs) and indoor residual spraying (IRS) are the

core vector-control options. Programs should prioritize the intervention most suitable for the local setting and deliver it at high coverage and to a high standard; IRS should be used where indoor-resting behavior, housing conditions, timing, and local insecticide-susceptibility data support its effectiveness. For Aedes-transmitted infections, including dengue, chikungunya, and Zika, priorities should include frequent emptying, scrubbing, covering, or removal of water-holding containers, safe management of household water storage and solid waste, and personal protection during the day, when Aedes mosquitoes commonly bite. These approaches should be adapted to local surveillance and implemented alongside community engagement and appropriate adult-mosquito control.

Successful IMM depends on continuous entomological surveillance, rapid identification of productive breeding sites, coordination among public-health, municipal, environmental, water, and agricultural sectors, community participation, and periodic evaluation of intervention effectiveness. This coordinated approach is particularly important where climatic variability, urban growth, environmental degradation, population displacement, and humanitarian pressures complicate mosquito-control operations.

Prioritize feasible community-led source reduction: empty, scrub, cover, or remove water-holding containers, safely manage household water storage, and remove discarded items that collect rainwater. These measures are especially relevant to Aedes transmitted infections and should be adapted to local water-access realities. Use existing health workers, community volunteers, and local leaders to share practical bite-prevention messages, encourage use and correct maintenance of insecticide-treated nets for malaria prevention, and promote repellents, protective clothing, and screens for daytime Aedes bite prevention where available.

4.4. Priority Actions for Sudan

4.4.1. Phase 1: Immediate, Low-Resource Actions

Prioritize feasible community-led source reduction: empty, scrub, cover, or remove water-holding containers, safely manage household water storage, and remove discarded items that collect rainwater. These measures are especially relevant to Aedes transmitted infections and should be adapted to local water-access realities. Use existing health workers, community volunteers, and local leaders to share practical bite-prevention messages, encourage use and correct maintenance of insecticide-treated nets for malaria prevention, and promote repellents, protective clothing, and screens for daytime Aedes bite prevention where available. Establish a simple, regularly updated reporting system using existing health-facility and community channels to record suspected outbreaks, locations of major breeding sites, and control activities. Prioritize accessible neighborhoods and sites where communities can safely participate.

4.4.2. Phase 2: Targeted Actions as Access and Logistics Permit

Direct limited staff, transport, and fuel to high-risk locations identified through available case reports, local observations, and feasible entomological checks; co-

ordinate visits with other public-health or humanitarian activities where possible. Use locally appropriate larval control only at persistent, productive breeding sites that cannot reasonably be eliminated or modified, and only where trained staff can apply approved products correctly and monitor implementation. During outbreaks or periods of high adult-vector density, consider targeted adult-mosquito control when operationally feasible. Select the method, timing, and insecticide according to vector behavior, local susceptibility information, product instructions, and the ability to protect residents and applicators.

4.4.3. Phase 3: Capacity-Dependent Strengthening

Restore and expand routine entomological surveillance, species identification, insecticide-susceptibility testing, and monitoring of intervention coverage and outcomes. These activities require trained personnel, supplies, transport, laboratory capacity, and sustained funding. Plan indoor residual spraying or other large-scale insecticide operations only where local vector behavior, housing conditions, susceptibility data, trained teams, procurement, transport, community access, and quality-assurance systems support safe and effective delivery. For malaria, maintain high-quality insecticide-treated-net delivery as a core intervention and use IRS selectively according to local evidence and programme capacity. Defer genetic, biological, or other novel vector-control technologies to appropriately governed research and pilot programs until regulatory oversight, ecological assessment, community engagement, and long-term monitoring can be assured.

4.5. Conclusion

Mosquito control in Sudan should move from isolated interventions toward coordinated, evidence-based management tailored to the vector and disease concerned. For malaria, insecticide-treated nets and appropriately selected indoor residual spraying are core interventions, with the choice guided by local vector behavior, insecticide susceptibility, and the feasibility of achieving high coverage. For Aedes-transmitted infections, source reduction should focus on water-holding containers and other productive breeding sites, supported by covering and weekly cleaning of essential water-storage containers, proper waste disposal, window and door screens, repellents, and protective clothing to reduce daytime bites. Improved drainage and sanitation remain useful where they address locally important breeding habitats, but environmental source reduction should not be presented as a universal substitute for disease-specific vector-control measures. Sustained surveillance, intersectoral coordination, community participation, and evaluation of intervention effectiveness are essential for durable mosquito control [70] [74] [75].

4.6. Limitations of the Study

This review is subject to important evidence limitations. Entomological surveillance and published evaluations from Sudan are incomplete and uneven across locations and periods, and conflict-related insecurity, displacement, restricted ac-

cess, and shortages of staff and supplies may further limit the representativeness and timeliness of available data. Consequently, the documented distribution of vector species, insecticide-resistance patterns, and reported intervention outcomes may not reflect current conditions throughout the country. In addition, some operational recommendations are informed by studies and guidance from other settings; their effectiveness in Sudan may vary with local vector behavior, housing, climate, water-storage practices, health-service capacity, and the feasibility of sustained implementation. Recommendations should therefore be interpreted as evidence-informed priorities rather than proof that every intervention will be effective in every Sudanese setting. Local surveillance, implementation monitoring, and context-specific evaluation are needed to refine these priorities.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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