Green Approaches to Mosquito Control: A Comprehensive Review

ABSTRACT

Mosquito-borne diseases pose significant health risks to humans and animals worldwide. Traditional methods of mosquito control often rely heavily on chemical pesticides, which not only harm the environment but also lead to the development of pesticide-resistant mosquito populations. In response to these challenges, there has been a growing interest in exploring eco-friendly approaches to mosquito control. This review paper aims to examine various green strategies for combating mosquitoes, focusing on their effectiveness, environmental impact, and feasibility for large-scale implementation and discuss methods such as biological control using natural predators and pathogens, habitat modification, utilization of botanical repellents, genetic manipulation of mosquito populations, and community-based interferences. Additionally, highlight the importance of integrated pest management (IPM) strategies that combine multiple tactics for sustainable mosquito control. By exploring these alternative methods, this review provides insights into promoting environmentally responsible practices while effectively managing mosquito populations and reducing the spread of mosquito-borne diseases.

Keywords: *Aedes aegypti, Bacillus thuringiensis,* Biological control, Biopesticides, Botanicals, Entomopathogenic Fungi, Mosquito trap.

1. INTRODUCTION

Mosquitoes are derived from the Spanish word "Musketas," which means "small fly," and these arthropods have a worldwide distribution. Species are classified into genera based on their physical traits. Mosquitoes are one of the deadliest insects in the world, there are over 3500 species all over the earth except in antarctica [1]. Temperature and species characteristics determines the life cycle from 1 to 20 days. Its life cycle consists of four main stages: Eggs last 2-3 days, larvae 8-9 days, pupae 1-2 days, and adults 10 days. The adult is active and lives on land, whereas the larvae and pupae live only in water [2]. Globally, malaria cases and mortality increased dramatically in 2022 compared to 2019 before the COVID-19 epidemic. Malaria incidences worldwide decreased from 243 million in 2000 to 233 million in 2019. In 2022, the number of cases reached approximately 249 million. The COVID-19 pandemic led to an increase of 55,000 deaths in 2020, bringing the total to 631,000 [3]. Vectors are living organisms that can spread infections or diseases between humans and animals. Vectors, such as arthropods, spread disease-causing germs by feeding on the blood of infected hosts (animal or human) and then spreading to new victims with their next meal. The mosquito is humanity's deadliest animal, causing over a million deaths each year by carrying malaria, Zika, yellow fever and a variety of other diseases [1] with the bulk of mortality happening in underdeveloped countries [4]. Mosquito-borne diseases, such as human malaria, dengue fever, chikungunya fever, Zika virus (ZIKV) sickness, and lymphatic filariasis, (Table 1) pose a significant threat to global health [5,6].

Vector control tactics have historically concentrated on killing mosquitos with a variety of insecticides. As insecticide resistance spreads across mosquito species, there is an increasing demand for safe, new, low-cost, and dependable mosquito control tactics [7]. Insecticide resistance in mosquitos is endangering the efficiency and sustainability of malaria control efforts around the world. Biological approaches present interesting alternatives to chemical control. They include natural mosquito killers, plant-based insecticides, releasing mosquitoes that are either sterile or unable to transmit disease, and erecting protective barriers against them [8].

There are 404 mosquito species identified in India, divided into 50 genera [9]. The major species that transmits diseases are *Anopheles culicifacies, A. minimus, A. philippinensis, , A . stephensi, Aedes aegypti, A. albopictus, Culex tritaeniorhynchus, C. annulirostris, C. tarsalis, C. quinquefasciatus, Mansonia indiana, M. uniformis* and *M. annulifera* etc [10].

Table 1. Species transmitting diseases in India

Vector	Disease	Pathogen transmitted	References
A. aegypti	Dengue fever (DHF) Chickungunya Zika Yellow fever	Virus	10,11
Anopheles *Culex*	Malaria Filariasis	Round worms *Plasmodium* sp.	10,11
Culex spp.	West nile virus	Virus	10,11
C. tritaeniorhynchus	Japanese encephalitis	Virus	10,11
C. annulirostris *A.vigilax*	Ross river fever	Virus	11

Present day vector control programs are focused on spraying chemicals. Despite the environmental and health problems, mosquitoes develop resistance to chemicals. In order to encompass these adversities it is better to choose eco-friendly green approaches. The green approaches include biological control (pathogens and predators), botanical insecticides, insect sterile techniques, physical methods and mechanical methods of control (12).

2. GREEN METHODS TO COMBAT MOSQUITOES

The methods include, role of pathogens including, entomopathogenic bacteria and fungi. Role of predators which covers, dipterans, coleopteran, hemipterans, odonatan, larvivorous fishes, frogs and toads. Incompatible insect technique, sterile insect technique, nano technological approach and role of botanicals (*Lantana camara,* marigold and periwinkle).

2.1 Role of Pathogens

2.1.1 <u>Entomopathogenic bacteria</u>

2.1.1.1 *Bacillus thuringiensis (Bt)*

B. thuringiensis (Bt) is a gram-positive, spore-forming, aerobic bacteria found in a wide range of environments. Bt serovarieties with larvicidal activity for Lepidoptera, Coleoptera, Diptera, and other insects have been isolated from a variety of habitats around the world, including dead insects, soil, the phylloplane, grain dust, aquatic, and other environments [13]. The mosquitocidal bacteria *B. thuringiensis subsp. israelensis* is more efficient than *B. sphaericus* as a larvicide against a wide range of mosquitoes and has been used consistently in various pest and vector management programs for over 20 years [14]. This bacterial bio-pesticide appears to last longer in the environment, especially in unclean water, and hence could be a feasible choice for long-term mosquito control (15,16)

The main insecticidal component of *B. thuringiensis subsp. israelensis* is a spherical parasporal body formed during sporulation and made up of four primary endotoxin proteins: Cyt1Aa, Cry4Aa, Cry4Ba, and Cry11Aa. This parasporal body is one of the most insecticidal known, with an LC50 value of 10 ng mL-1 against several mosquito species' fourth instars. *Bacillus thuringiensis* (Bt) causes damage to insect guts when swallowed by vectors. Shortly after ingestion, these proteins bind to and lyse insect midgut epithelial cells, resulting in death. Ingestion of activated toxic protein (granular formulation) of Bti was extremely toxic to Anopheles, Culex, and Aedes larvae, causing cell membrane lining disintegration in the midgut (Fig. 1). *Bt israelensis* at 0.006 - 0.662 mg L-1 (LC50) caused 50% mortality of *A. gambiae* [17].

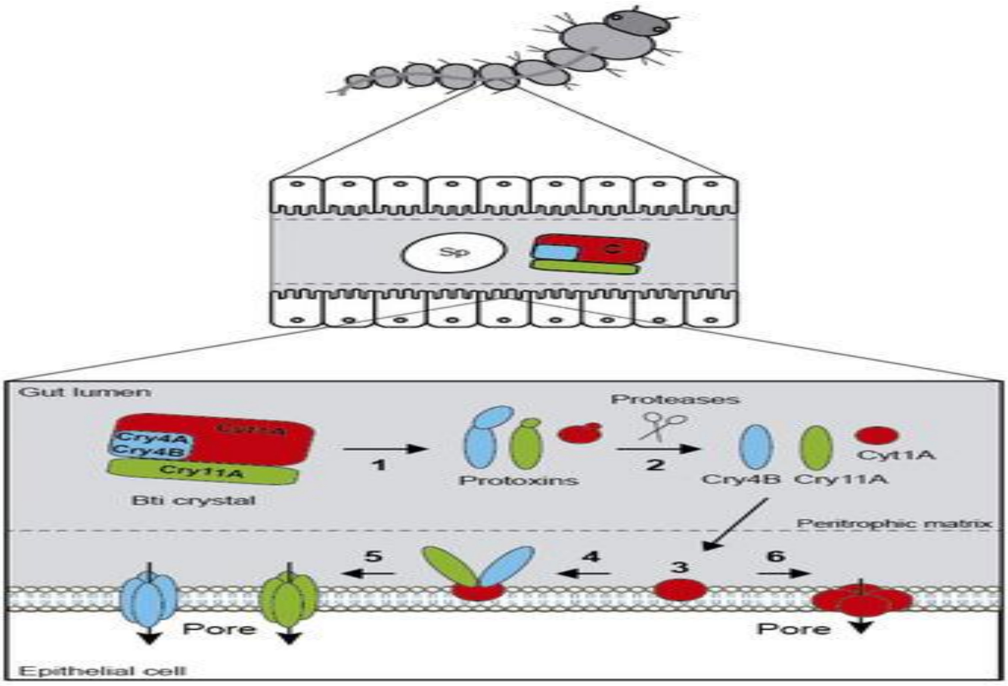

Fig. 1. Mode of action of *Bacillus thuringenesis* [18]

2.1.1.2. *Bacillus sphaericus*

B. sphaericus is a gram-positive, spore-forming, aerobic bacterium found in a wide range of soil and aquatic environments. The moiety that causes mosquito larvicidal activity in serovar. 5a5b isolates of *B. sphaericus* are binary toxins [16]. Proteins are essential for complete toxicity in the host. Similarly to Bti, ingested poisons are solubilized in the alkaline midgut and cleaved to the active moiety by proteases. The toxin's two component proteins, Bin A (42k Da) and Bin B (51k Da), bind to specific receptors on the brush border of epithelial cells in the gastric caecum and midgut, causing pore formation (permeabilization), disrupting osmotic balance, cell lysis, and, ultimately, insect death. *B. sphaericus* at 0.002-0.342 mg L-1 (LC50) caused 50% death, while *A. gambiae* at 0.018-1.807 mg L-1 (LC95) caused 95% mortality [19]. *B. sphaericus* is completely safe for humans, animals, wildlife, and the environment, and is ideal for communal use [20]. Unlike Bti, which has no known field resistance, *B. sphaericus* crystal toxin resistance has been observed in Culex larvae [21]. As a result, the recent rise of resistance has complicated mosquito control efforts.

Mazigo [22] conducted an experiment to evaluate the time of application of a biolarvicide, *Bacillus thuringiensis israelensis* (Bti), and fertilizer (di-ammonium phosphate-DAP or urea), and to analyze their effect on mosquito larval density and rice crop yields. The findings of this study indicate that applying Bti and fertilizer at 7-10 day intervals reduces mosquito larvae density in rice fields. This suggests that the Bti was only effective for 7–10 days.

2.1.2 <u>Entomopathogenic fungi</u>

Recent research has highlighted the potential of entomopathogenic fungus in suppressing malaria vectors. These fungi do not induce immediate death, but instead have sublethal and late-life lethal effects on various phases of the mosquito life cycle. Because of these features, fungi have the potential to be utilized as "evolution proof" agents, overcoming mosquito resistance in contrast to the currently used fast-acting chemical insecticides [22]. Beauveria, Pythium, Metarhizium, Leptolegnia, Coelomomyces, Lagenidium and Conidiobolus are the most regularly reported genera to have an effect on mosquitos.

In adult mosquitos, the conidia connect to the host cuticle, forming an appressorium before entering the cuticle via a penetration peg (Fig. 2). After entering the hemocoel, hyphae develop and release toxins, killing the host within 4-16 days of exposure. In aquatic insects, fungal conidia enter the spiracles, germinate, and pierce the respiratory siphon, releasing poisons by impeding the breathing mechanism [23]. When applied to water bodies, the hydrophobic conidia float on the surface and come into contact with mosquito larvae via the siphon's tip and head. When floating conidia come into touch with larvae, their peri spiracular valves allow them to breathe by breaking the water tension. Plugging the spiracles usually results in death before major invasion of the hemocoel occurs, therefore hyphal body production is limited [24].

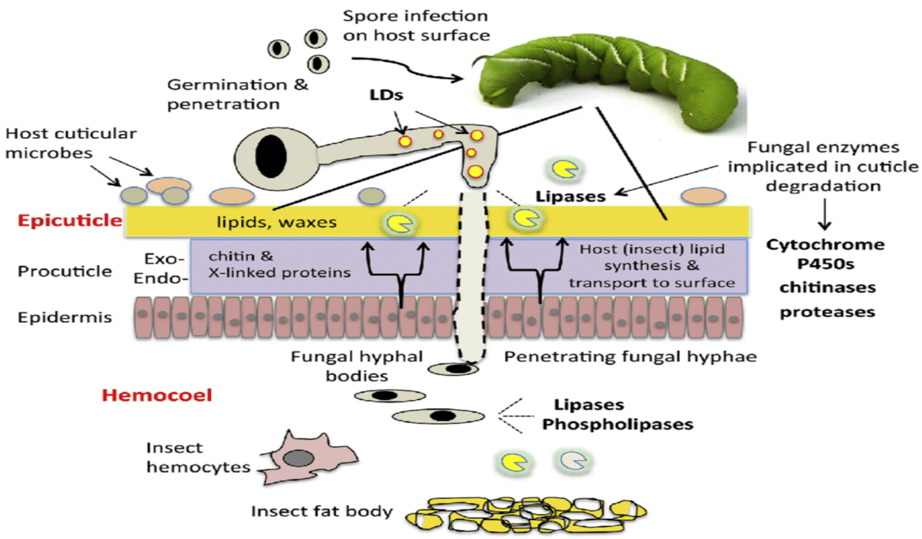

Fig. 2. Mechanism of Infection of Entomopathogenic Fungi [26]

2.1.3 <u>Microbial formulations used in mosquito control</u>

One of the key components to the commercial success of a biological control agent is formulation. The development of a good formulation is important for the successful utilization of commercial biopesticides. Commercial Bt formulations used to control mosquitos (Table 2) [27].

1. Water Dispersible Granules (WDG)
2. Aqueous Suspensions (AS)
3. Granules (G) Briquets
4. Icy granules.

Table 2. Commercial formulations of *Bacillus sps*.

Bt sub sp.	Commercial Formulation	Producer	Dose	References
Bt israelensis	VectoBac [AS]	Abbott Laboratories	0.3-6.0 l/ha	[28]
	Vectobac [WDG]	Valent Biosciences corporation	@ 300 g/ha	[29]
	Culinex tablets		1 tablet/2000 l	[30]
	Vectobac [G]	Abbott Laboratories	2-20 kg/ha	[28]
	FourStar™ briquets	Best chemical Co(s) Pte Ltd	1 briquette/100 ft^2	[19]
B. sphaericus	Vectolex WDG	Valent Biosciences corporation	400 g/ha	[19]
	VectoBac 12AS	ADAPCO, Azelis company	0.5 – 1L /ha	[19]

Abbreviations: *Bti*, *Bacillus thuringiensis* var. *israelensis*; *Bs*, *Bacillus sphaericus*; AS, aqueous suspension; G, granules; WDG, water-dispersible granules.

2. 2 Role of Predators in Mosquito Control

Predatory insects that feed on mosquito larvae and pupae in aquatic situations can help reduce Culicidae populations [31]. A variety of aquatic creatures prey on young instars, including mosquito larvae from other species, copepods, odonate young instars, water bugs, amphibians, and fish [30].

2.2.1 Dipteran predators

Toxorhynchites spp., also known as the "elephant mosquito" or "mosquito eater", is a big, worldwide mosquito genus that does not swallow blood. While the adults consume sugar-rich items such as honeydew, fruit, and nectar, the larvae feed on the larvae of other mosquitos and other nektonic (free swimming) creatures. Toxorhynchites adults are larger than Aedes and thought to be harmless to humans [33].

2.2.2 Coleopteran predators

Dytiscidae and Hydrophilidae are coleopteran families that have been studied as mosquito larvae predators. Dytiscidae and Hydrophilidae adults and larvae are common predators in ground pools, ponds (both permanent and temporary), and artificial mosquito breeding areas. Aditya [34] identified Laccophilus, Agabus, and Rhantus as possible biological control agents for mosquitos. A recent field study [35] found that *Acilius sulcatus* (Family: Dytiscidae) larvae have a considerable impact on mosquito larvae *C. quinquefasciatus, C. vishnui, C. bitaeniorhynchus, C. gelidus, C. tritaeniorhynchus, Anopheles annularis, A. subpictus, A. barbirostris and Armigeres subalbatus* that prevail in cement tanks.

2.2.3 Hemipteran predators

Predaceous Hemipteran bugs are classified into three major families: Belostomatidae, Nepidae, and Notonectidae. Back swimmers (Family: Notonectidae) are the most prevalent bugs that feast on mosquito larvae, making them an essential component in reducing young mosquito populations and considered promising for mosquito control [36].

2.2.4 Odonatan predators

Odonata larvae are fierce predators of mosquito larvae in watery settings. Dragonfly larvae are known to eat significantly on bottom feeder mosquitoes, such as Aedes larvae. Sebastian [37] discovered that using dragonfly larva, *Labellula sp*., full elimination of all *A. aegypti* larvae and pupae was obtained between days 4 and 9, depending on the density of aquatic stages of mosquitoes present per container [38].

2.2.5 Larvivorous fishes

Biological mosquito control with vertebrates has been focused on the role of larvivorous fish, which consume mosquito larvae in the aquatic stage [31]. Fish predation on mosquito larvae has been seen in a variety of habitats, ranging from small plastic containers to complex natural ecosystems, including coastal wetland environments [39]. Gambusia and Poecilia (Poeciliidae) have been introduced to more than 60 nations for mosquito control. Salim [40] discovered that the quantity of larvae was reduced in the intervention ponds. The greatest reduction in Anopheles larvae devoured by *G. affinis* was 100% after one month, followed by 83.3% in a fortnight.

2.2.6 Frogs and toads

Tadpoles with varying life histories actively hunt on A. aegypti's eggs. It has been demonstrated that this mosquito species prefers to lay eggs in tadpole water, and that tadpoles from the Polypedates cruciger, Bufo, Ramanella, Euphlyctis, and Hoplobatrachus genera prey on the eggs [41].

2.3 Incompatible Insect Technique

Cytoplasmic incompatibility (CI) is a situation in which sperm and eggs are unable to produce viable progeny. The effect is caused by alterations in the gametes of Wolbachia-infected males. Wolbachia changes sperm prior to spermatogenesis and interferes with the parental chromosomes during the initial mitotic divisions, causing them to split out of sync. Because of the sensitive relationship between mosquito survival and vectorial capacity, interventions aimed at reducing adult mosquito daily survivorship, such as residual insecticide spraying in homes and insecticide-treated bed nets for malaria control, result in significant reductions in pathogen transmission rates. A strain of the obligatory intracellular bacteria *Wolbachia pipientis*, wMelPop, has been identified that shortens the adult life span of its natural fruit fly host, *Drosophila melanogaster*. It has been hypothesized that life-shortening wolbachia strains, such as wMelPop, might be employed to shift the age structure of the mosquito population toward younger individuals, lowering pathogen transmission but not destroying the population. Wolbachia are maternally inherited bacteria that exploit processes including cytoplasmic incompatibility (CI), a type of embryonic mortality caused by crosses between infected males and uninfected females, to rapidly spread throughout insect communities. Evidence from other Wolbachia insect [42] interactions suggests that CI may allow wolbachia strains, such as wMelPop, to infect mosquito populations even if they impose a fitness penalty, such as increased mortality. Current simulations

Table 3. ***Wolbachia strains infect mosquitos.***

Strain	Original host	Transinfected	Effect on host insect	Reference

		host		
wMelPop-CLA	*Drosophila melanogaster*	*A. aegypti*	Cytoplasmic Incompatability, Life shortening, Blood-feeding alteration Bendy proboscis	[42]
wMelPop	*Drosophila melanogaster*	*A. albopictus*	life shortening, embryo mortality	[42]
wPip	*Culex pipiens*	*A. albopictus*	CI, lower hatch rate, reduced fecundity	[43]

suggest that this method could lead to considerable reductions in disease transmission. However, life-shortening Wolbachia strains are not found naturally in mosquitos. Stable introduction of a life-shortening Wolbachia infection into the mosquito Aedes aegypti resulted in a shorter life span for all mosquitos and induced cytoplasmic incompatibility, resulting in non-viable offspring when crossed with an infected male, reducing mosquito populations [42].

2.4 Sterile Insect Technique

There are no specific treatments or licensed vaccines for dengue, thus attempts to limit transmission rely primarily on vector management [44]. The current control measures are jeopardized by the actual or potential spread of resistance in the vector population. As a result, new ways must be developed expeditiously. The introduction of transgenic vectors may open up new avenues for lowering the density or vectorial capacity of vector populations [45]. Insect Technique (SIT) is a genetic control approach that involves the release of a large number of radiation-sterilised insects. These mate with wild insects of the same species, reducing the reproductive capacity of the wild pest population by producing no or fewer viable offspring as a result of radiation-induced lethal mutations in their gametes [46, 47]. Although successful against certain agricultural pests, attempts against mosquitos have been less successful. This is due in part to the somatic damage and performance loss in sterile insects that unavoidably occurs with radiation sterilization. Interestingly, one effective case of SIT in mosquitos used a chemosterilant instead of radiation [48].

Modern genetics has the potential to overcome this problem, for example, by using an engineered self-limiting gene that is both repressible by an antidote provided in a managed rearing facility and, when expressed in the absence of the repressor, causes mortality before the insect reaches functional adulthood, which could be used in place of radiation [49]. Operationally, the system would be quite similar to SIT, with the same clean, species-specific qualities and benefiting from the released males' female-seeking abilities. However, the insects would not be irradiated; rather, they would be homozygous for a transgene, which, when passed to an embryo via sperm, would cause the zygote to die at some stage in development [50]. In addition to minimizing the requirement for radiation, altering the timing of death can improve efficiency versus target populations with high density dependence. Simulation modeling reveals that such an approach could potentially be successful and economical against *Aedes aegypti* [48].

According to Carvalho [48], SIT with self-limiting genetic technology is a promising strategy. OX513A, a self-limiting strain of *Aedes aegypti,* has previously been field evaluated. In 2010, sustained releases of OX513A A. aegypti males resulted in an 80% suppression of the target wild *A. aegypti* population in the Cayman Islands. Sustained release of OX513A males has the potential to be a practical and efficient strategy for inhibiting the primary dengue vector*, A. aegypti*. In the tested locality and other areas with comparable or lower transmission, the reported degree of suppression would probably be adequate to stop dengue epidemics [48].

2.5 Nano Technological Approach

Over the last decade, nanocomposite (NCs) has gained popularity in a variety of commercial products due to its several advantages over nanoparticles. There are several types of NCs based on the combination, such as metal/polymer, metal/metal oxide, and Bio-NC, which combines a metal nanoparticle with bio-compounds as a solid supporting matrix [51]. Despite the fact that a wide range of solid supportive matrixes, such as porous carbon material, inorganic clay, silica, and zeolite, have been used to synthesize silver nanocomposite to take advantage of their surface functional group and anchor nanoparticles to exploit their novel potential [52]. As a result, the development of novel biodegradable, environmentally friendly, and targeted larvicides is critical for future control tactics. In this regard, the scientific community strongly supports the bio-synthesis of Ag-NC using low-value biowaste as a solid support material and crystallizing metal by hydrothermal treatment. Hydrothermal synthesis is typically performed at high vapor pressure levels and with a high-temperature aqueous solution, hence the name 'Hydro' + 'Thermal' = Hydrothermal technique.

Sundaramahalingam [53] produced silver nanoparticles (AgNPs-RH) and impregnated them on the surface of rice husk, which was then molded into a clay coin for the steady-state release of Ag ions from a porous terracotta disc (PTD) against mosquito larvae in water. They concluded that 24 hours of exposure to the intended PTD resulted in 100% larvicidal death, and the amount of silver released from the porous disc was 0.0343 ppm. Furthermore, histological investigations of dead larvae demonstrated that silver ions from the PTD had significantly damaged the larvae's exoskeleton.

2.6 Role of Botanical Insecticides in Mosquito Control

Plant-based mosquito larvicides have been shown to outperform synthetic insecticides in mosquito control programs, reducing environmental risks. To date, 344 species have been documented to show substantial activity against mosquitos [54]. Common mosquito control plants include *Acacia nilotica*, *Lantana camera*, *Catharanthus roseus* G., *Clerodendrum phlomidis*, *Curcuma longa*, *Tagetes patula*, *Cymbopogon citrates* etc.

2.6.1 Lantana (*Lantana camara L.)*

Lantana oil and crude extract are natural fumigants that repel a variety of insects and mosquitos. Lantana leaves contain primarily (triterpenoids), Oleanonic acid, icterogenin, Lantadene A, Lantadene B, Lantanilic acid and 4,5-dihydroxy3,7-dimethoxyflavone-4-o-betaDglucopyranoside, Camaroside. These chemicals were responsible for the repellent property [54].

2.6.2 Marigold (*Tagetes patula* Linn.)

Tagetes' chemical contents include β-karyophyllene, terpenes, hydrocarbons, alcohols, ethers, aldehydes, ketones, esters, carotenoids, flavonoids, and thiophenes. They offer insect repellents, antiseptics, diuretics, blood purifiers, and cancer treatments [55]. The extract of *T. patula* is effective over the larvae and pupae of *A. aegypti* at lower concentations [55].

2.6.3 Periwinkle (*Catharanthus roseus* L.)

Its leaves contain two secondary metabolites, vincristine and vinblastine, which have larvicidal activity against *Culex spp*. [56].

Kokila [55] investigated the insecticidal and biological effects of three plant extracts on the dengue vector, *A. aegypti* (Diptera: Culicidae). They found that Periwinkle (*Catharanthus roseus* L.) leaves showed larval and pupal mortality of *A. aegypti* after treatment with methanol extract of *C. roseus* leaf extract at various concentrations (2 mg L -1, 4 mg L -1, 6 mg L -1, 8 mg L -1, and 10 mg L -1). At a dosage of 10 mg L-1, 89 percent of the larvae died in the first instar.

Mortality varied significantly throughout the concentrations tested. The lowest measured LC50 was 5.89 mg L-1 for the I instar, while the highest was 6.87 mg L-1 for the IV instar. In comparison to *A. aegypti's* III and IV instars, the pupae were more sensitive [55]. Agnimantha (*Clerodendrum phlomidis*) flowers contain secondary metabolites such as tannins, alkaloids, polyphenols, terpenoids, and essential oils, which have larvicidal effect against mosquitos. *A. aegypti* larval and pupal death rates ranged from 12 to 85% [55]. Marigold (*Tagetes patula* Linn.) is effective against larvae and pupae at low concentrations ranging from 5 mg L -1 to 7 mg L-1. Early instars were more vulnerable to *T. patula* than later instars [55]. *T. patula* extract had a little greater death rate when compared to *C. phillomedis* and *C. roseus*, but there was no significant difference between the three test plants.

2.6.4 Botanical formulations used for mosquito control

2.6.4.1 Neo-Innova®

Neo-Innova® is a repellent with a long-lasting effect. "NEO-PART®" (Prolonged Action Release Technology) is a formulation containing 40% Citriodiol®. It comprises the chemical para-menthane 3,8-diol (PMD) at 25% w/v. In A. aegypti, the full protection period (CPT; 14.2 h) was around two to three times longer than that reported in other formulations sold in the United States, including a 25% deet and a 20% PMD ethanolic formulation [57].

2.6.4.2 ME 750

Smyrnium olusatrum contains isofuranodiene and essential oils with larvicidal properties. Isofuranodiene synthesized in ME 750 was effective against *C. quinquefasciatus* at an LC50 of 18.6 µL L-1, resulting in considerable larval mortality over time and a marked decrease in adult emergence [58].

3. PHYSICAL METHODS

It is the change of physical components in the environment to reduce or eliminate mosquito populations, which includes changing the water in birdbaths, pools, fountains, and rain barrels once a week. Screening doors and windows to defend against mosquito attacks. Mosquito net These nets are regarded as more protective than coils and other repellents because their use poses no health risk (59). There are two types of nets: medicated and non-medicated [60].

4. MECHANICAL METHODS

4.1 Mosquito Traps

These traps mimic numerous mosquito attractants, including body heat and exhaled carbon dioxide. They are powered by electricity, therefore their operation is safe. When a mosquito is drawn to an impeller fan, it attaches to the sticky surface of the trap and is shocked [61]

a)Mosquito trap b) Mosquito magnet c) Electric mosquito zipper

Fig 3. Mechanical methods of mosquito control [62]

4.2 Electric Mosquito zipper

This device operates by emitting UV light, which kills mosquitos when they interact with a deadly electric charge [62].

4.3 Mosquito Magnet

Its approach is based on mimicking mammal features such as emitting heat, moisture, and carbon dioxide. When a mosquito gets close to the gadget, it draws in and dies [62].

5. CONCLUSION

Eco-friendly mosquito control measures are required to limit the long-term administration of insecticides, which is currently the dominant strategy for mosquito control. Safe and sustainable approaches for targeting various mosquito species, including bioagents, predators, insect sterile techniques, physical and mechanical methods, should be developed such that they are accessible to the general public. The need-based production of biocontrol formulations such as tablets, capsules, ice granules, and so on should be promoted.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

1. Hawkes FM, Hopkins RJ. The mosquito: An introduction. Mosquitopia. 2021 Sep 1:16-31.

2. Floore T. Mosquito information. The American Mosquito Control Association Pherec. 2002.

3. World Health Organization. WHO malaria policy advisory group (MPAG) meeting report, 18–20 April 2023. World Health Organization; 2023 Jun 1.

4. Yang X, Quam M B M, Zhang T, Sang S. Global burden for dengue and the evolving pattern in the past 30 years. J Travel Med. 2021;28:1-11

5. Franklinos LH, Jones KE, Redding DW, Abubakar I. The effect of global change on mosquito-borne disease. Lancet Infect Dis. 2019;19(9):e302-e312.

6. Jones RT, Ant TH, Cameron MM, Logan JG. Novel control strategies for mosquito-borne diseases. Philos Trans R Soc B, Biol Sci. 2021;376(1818):20190802.

7. Govindarajan M, Benelli G. One-pot green synthesis of silver nanocrystals using Hymenodictyon orixense: a cheap and effective tool against malaria, chikungunya and Japanese encephalitis mosquito vectors. RSC adv. 2016;**6**(64):59021-59029.

8. Suh PF, Elanga-Ndille E, Tchouakui M, Sandeu MM, Tagne D, Wondji C, Ndo C. Impact of insecticide resistance on malaria vector competence: a literature review. Malaria Journal. 2023 Jan 17;22(1):19.

9. Tyagi BK, Munirathinam A, Venkatesh A. A catalogue of Indian mosquitoes Int J Mosq Res. 2015;2(2):50-97.

10. World Health Organization. Fact sheets on vector-borne diseases in India. World Health Organization. 2014;1-24

11. Naik BR, Tyagi BK, Xue RD. Mosquito-borne diseases in India over the past 50 years and their Global Public Health Implications: A Systematic Review. Journal of the American Mosquito Control Association. 2023 Dec 1;39(4):258-77.

12. Benelli G, Jeffries CL, Walker T. Biological control of mosquito vectors: past, present, and future. Insects. 2016;7(4):52.

13. Damgaard PH. Natural occurrence and dispersal of *Bacillus thuringiensis* in the environment. In: Entomopathogenic Bacteria: from laboratory to field application. Charles JF, Delecluse A, Nielsen-LeRoux C. (eds). Dordrecht: Kluwer Academic Publishers. 2000;23–40.

14. Goldberg LJ, Margalit J. A bacterial spore demonstrating rapid larvicidal activity against *Anopheles sergentii, Uranotaeni aunguiculata*, *Culex* univitattus, *Aedes aegypti* and *Culex univitattus*. Mosq. News. 1977;**37**:355–358.

15. Prasad A, Kumar D, Srivastava M, Sharma E, Mathur PC. Soil Bacteria and their Possible Role in Mosquito Control: A Short Review. World J Environ Biosci. 2013;2(1):40-48.

16. Gangmei K, Bora B, Mandodan S, Abhisubesh V, Aneha K, Manikandan S, Lukose J, Hemaladkshmi P, Mathivanan A, Vijayalakshmi K, Poopathi S. A Review on Vector Borne Diseases and Various Strategies to Control Mosquito Vectors: Current strategies to control mosquito vectors. Indian J Entomol. 2023.

17. Boyce R, Lenhart A, Kroeger A, Velayudhan R, Roberts B, Horstick O. Bacillus thuringiensis israelensis (B ti) for the control of dengue vectors: Systematic literature review. Trop. Med. Int. Health. 2013;18(5):564-77.

18. Valtierra-de-Luis D, Villanueva M, Berry C, Caballero P. Potential for Bacillus thuringiensis and other bacterial toxins as biological control agents to combat dipteran pests of medical and agronomic importance. Toxins. 2020 Dec 5;12(12):773.

19. Derua YA, Kweka EJ, Kisinza NW, Githeko AK, Mosha FW. Bacterial larvicides used for malaria vector control in sub-Saharan Africa: review of their effectiveness and operational feasibility. Para. Vect. 2019;**12**:426.

20. El-Bendary M, Priest FG, Charles JF, Mitchell WJ. Crystal protein synthesis is dependent on early sporulation gene expression in Bacillus sphaericus. FEMS microbiol lett. 2005;252(1):51-6.

21. Gilbert LI, Gill SS. Insect control: biological and synthetic agents. Academic Press. 2010.

22. Mazigo HD, Mboera LE, Rumisha SF, Kweka EJ. Malaria mosquito control in rice paddy farms using biolarvicide mixed with fertilizer in Tanzania: semi-field experiments. Malar J. 2019;18:1-0.

23. Read AF, Lynch PA, Thomas MB. How to make evolution-proof insecticides for malaria control. PLoS Biol. **2009; 7**:e1000058.24 .

24. Lacey CM, Lacey LA, Roberts DR. Route of invasion and histopathology of *Metarhizium anisopliae* in *Culex quinquefasciatus.* J invertebr pathol. 1988;52(1):108-18.

25. Qin Y, Liu X, Peng G, Xia Y, Cao Y. Recent advancements in pathogenic mechanisms, applications and strategies for entomopathogenic fungi in mosquito biocontrol. Journal of Fungi. 2023 ;9(7):746.

26. Keyhani NO. Lipid biology in fungal stress and virulence: Entomopathogenic fungi. Fungal biology. 2018 Jun 1;122(6):420-9.

27. Rydzanicz K, Lonc E, Kiewra D, Dechant P, Krause S, Becker N. Evaluation of three microbial formulations against *Culex pipiens* larvae in irrigation fields in Wroclaw, Poland. J Am Mosq Control Assoc. 2009;25(2):140-148.

28. Obopile M, Segoea G, Waniwa K, Ntebela DS, Moakofhi K, Motlaleng M, et al. Did microbial larviciding contribute to a reduction in malaria cases in eastern Botswana in 2012–2013? *PHA.* 2018;**8**(Suppl. 1):50–54. doi: 10.5588/pha.17.0012. [PMC free article] [PubMed] [CrossRef] [Google Scholar]

29. Ingabire CM, Hakizimana E, Rulisa A, Kateera F, Van Den Borne B, Muvunyi CM, et al. Community-based biological control of malaria mosquitoes using *Bacillus thuringiensis* var. *israelensis* (Bti) in Rwanda: community awareness, acceptance and participation. *Malar J.* 2017;**16**:399. doi: 10.1186/s12936-017-2046-y. [PMC free article] [PubMed] [CrossRef] [Google Scholar] [Ref list]

30. Kahindi SC, Midega JT, Mwangangi JM, Kibe LW, Nzovu J, Luethy P, et al. Efficacy of vectobac DT and Culinexcombi against mosquito larvae in unused swimming pools in Malindi, Kenya. *J Am Mosq Control Assoc.* 2008;**24**:538–542. doi: 10.2987/5734.1. [PubMed] [CrossRef] [Google Scholar] [Ref list]

31. Griffin LF, Knight JM. A review of the role of fish as biological control agents of disease vector mosquitoes in mangrove forests: Reducing human health risks while reducing environmental risk. Wetl. Ecol. Manag. 2012;20:243- 252.

32. Subramaniam J, Murugan K, Panneerselvam C, Kovendan K, Madhiyazhagan P, Kumar PM, Dinesh D, Chandramohan B, Suresh U, Nicoletti M, Higuchi A. Eco-friendly control of malaria and arbovirus vectors using the mosquitofish *Gambusia affinis* and ultra-low dosages of Mimusops elengi-synthesized silver nanoparticles: towards an integrative approach. Environ Sci Pollut Res Int. 2015 ;2:20067-83.

33. Kumar PM, Murugan K, Madhiyazhagan P, Kovendan K, Amerasan D, Chandramohan B, Dinesh D, Suresh U, Nicoletti M, Alsalhi MS, Devanesan S. Biosynthesis, characterization, and acute toxicity of *Berberis tinctoria* fabricated silver nanoparticles against the Asian tiger mosquito, *Aedes albopictus,* and the mosquito predators *Toxorhynchites splendens* and *Mesocyclops thermocyclopoides*. Parasitol. Res. 2016;115:751-9.

34. Aditya G, Saha GK. Predation of the beetle *Rhantus sikkimensis* (Coleoptera: Dytiscidae) on the larvae of *Chironomus Meigen* (Diptera: Chironomidae) of the Darjeeling Himalayas of India. Limnologica. 2006;*36*(4):251-257.

35. Chandra G, Mandal SK, Ghosh AK, Das D, Banerjee SS, Chakraborty S. Biocontrol of larval mosquitoes by *Acilius sulcatus* (Coleoptera: Dytiscidae). BMC Infec. Dis. 2008;**8**:138.

36. Allo NM, Mekhlif AF. Role of the predator Anisops sardea (Hemiptera: Notonectidae) in control mosquito Culex pipiens molestus (Diptera: Culicidae) population.

37. Sebastian A, Thu MM, Kyaw M, Sein MM. The use of dragonfly nymphs in the control of *Aedes aegypti*. Trop Med Public Health. 1980;11(1): 104-107.

38. Saha N, Aditya G, Banerjee S, Saha GK. Predation potential of odonates on mosquito larvae: Implications for biological control. Biological Control. 2012 Oct 1;63(1):1-8.

39. Harrington RW, Harrington ES, Effects on fishes and their forage organisms of impounding a Florida salt-marsh to prevent breeding by saltmarsh mosquitos. Bull. Mar. Sci. 1982;32:523-531.

40. Salim OAA, Hassan AEM, Bala ADA. Efficacy of the Mosquito fish, *Gambusia affinis* (Baird and Girard) in the Control of *Anopheles* and *Culex* Mosquito larvae in Sennar State. Sudan U K J Agric Sci. 2015;23(1):33-48.

41. Bowatte G, Perera P, Senevirathne G, Meegaskumbura S, Meegaskumbura M. Tadpoles as dengue mosquito (Aedes aegypti) egg predators. Biol Control. 2013;67(3):469-74.

42. McMeniman CJ, Lane RV, Cass BN, Fong AW, Sidhu M, Wang YF, O'Neill SL. Stable introduction of a life-shortening *Wolbachia* infection into the mosquito *Aedes aegypti*. Sci. **2015;323**(5910):141-144.

43. Calvitti M, Moretti R, Skidmore AR, Dobson SL. Wolbachia strain w Pip yields a pattern of cytoplasmic incompatibility enhancing a Wolbachia-based suppression strategy against the disease vector Aedes albopictus. Parasites & vectors. 2012 Dec;5:1-9.

44. WHO T. Dengue: guidelines for diagnosis, treatment, prevention and control. Geneva: WHO Library. 2009:10-2.

45. Harris AF, McKemey AR, Nimmo D, Curtis Z, Black I, Morgan SA, et al. Successful suppression of a field mosquito population by sustained release of engineered male mosquitoes. Nat Biotech. 2012;30(9):828–30.

46. Dyck VA, Hendrichs J, Robinson AS. Sterile insect technique: principles and practice in area-wide integrated pest management. Netherlands: Springer; 2005.

47. Knipling E. Possibilities of insect control or eradication through use of sexually sterile males. J Econ Entomol. 1955;48:459–62.

48. Carvalho DO, McKemey AR, Garziera L, Lacroix R, Donnelly CA, Alphey L, Malavasi A, Capurro ML. Suppression of a field population of *Aedes aegypti* in Brazil by sustained release of transgenic male mosquitoes. PLoS negl trop dis. 2015;**9**(7):0003864.

49. Thomas DD, Donnelly CA, Wood RJ, Alphey LS. Insect population control using a dominant, repressible, lethal genetic system. Sci. 2000;287(5462):2474–6. PMID: 10741964

50. Catteruccia F, Crisanti A, Wimmer E. Transgenic technologies to induce sterility. Malaria J. 2009; 8(2):S7. doi: 10.1186/1475-2875-8-S2-S7 PMID: 19917077**.**

51. Yee-Shing L, Chang YC, Chen HH. Silver nanoparticle biosynthesis by using phenolic acids in rice husk extract as reducing agents and dispersants. J Food Drug Anal. 2018;26:649–56.

52. Granbohm H, Larismaa J, Ali S, Johansson LS, Hannula SP. Control of the size of silver nanoparticles and release of silver in heat treated SiO2-Ag composite powders. Materials. 2018;11(1):80.

53. Sundaramahalingam B, Mahboob S, Jain C, Marimuthu N, Manickaraj P, Al-Ghanim KA, Al-Misned F, Ahmed Z. Design and development of porous terracotta disc: An eco-friendly novel control agent for mosquito larvae. Exp. Parasitol. 2020;218:107988.

54. Remia KM, Logaswamy S. Larvicidal efficacy of leaf extract of two botanicals against the mosquito vector *Aedes aegypti* (Diptera: Culicidae). Indian J Nat Prod Resour. 2009;1(2):208-212.

55. Kokila R, Nareshkumar A, Meenambigai K, Nataraj B, Abdulla S, Shanmugapriya R, Chandhirasekar K, Manikandan AT. Insecticidal and biological effects of three plant extracts tested against the dengue vector, *Stegomyia agyptii* (Diptera: Culicidae). J. Entomol Acarol. Res. 2016;48(1):16-22.

56. Nejat N, Valdiani A, Cahill D, Tan YH, Maziah M, Abiri R. Ornamental exterior versus therapeutic interior of Madagascar periwinkle (*Catharanthus roseus*): the two faces of a versatile herb. Sci World J. 2015.

57. Carroll, A.R., Copp, B.R., Davis, R.A., Keyzers, R.A. and Prinsep, M.R., 2019. Marine natural products. *Natural product reports*, *36*(1), pp.122-173.

58. Pavela R, Pavoni L, Bonacucina G, Cespi M, Kavallieratos NG, Cappellacci L, Petrelli R, Maggi F, Benelli G. Rationale for developing novel mosquito larvicides based Isofuranodiene microemulsions. J Pest Sci. 2019;**92**(2):909-921.

59. Peterson C, Coats J. Insect repellents-past, present and future. Pes Outloo. 2001;12(10):154-158.

60. Impoinvil DE, Ahmad S, Troyo A, Keating J, Githeko AK, Mbogo CM, Kibe L, Githure JI, Gad AM, Hassan AN, Orshan L. Comparison of mosquito control programs in seven urban sites in Africa, the Middle East, and the Americas. Health Policy. 2007;83(2-3):196-212..

61. Sumithra V, Janakiraman A, Altaff K. Bio-control of mosquito larvae through the black molly, *poecilia sphenops.* Int J Pure App Zool. 2014;2(3):270-4.

62. Onyett H. Preventing mosquito and tick bites: A Canadian update. Paediatr child health. 2014;19(4): 329-33.