Chapter

Advances in Mosquito Control: A Comprehensive Review

Sarita Kumar and Arunima Sahgal

Abstract

Mosquitoes are the important global vectors transmitting diseases of human concern such as dengue, Chikungunya, Malaria, encephalitis and yellow fever, etc. Management of mosquito-borne diseases largely relies on the vector management because of the lack of effective medication and vaccination. Several strategies have been formulated and applied in the fields to control mosquitoes; yet there is a continued rise in mosquito-borne diseases leading to sufferings and morbidities. Presently, chemical interventions are the most preferred methods which has impacted human health and the environment negatively. These issues have created a demand to devise novel approaches which can be used safely and effectively for mosquito management. Thus, several innovative mosquito control interventions have been devised based on genetic, physical and behavioral modifications in mosquitoes. These strategies span from Sterile Insect Technique (SIT) Release of Insects Carrying a Dominant Lethal (RIDL), creating transgenics with abnormal and lethal genes, gene drive technology, reducing the vectorial capacity by *Wolbachia* infection and application of attractive toxic sugar baits (ATSB), or by lasers and light detectors to investigate their behavior, and enhance their trap and kill. This Chapter gives a comprehensive overview of the conventional, and novel and innovative techniques devised for the control of mosquito vectors.

Keywords: Mosquito control, SIT, *Wolbachia*, ATSB, Transgenics, Gene drive, RIDL, Laser, Conventional strategies

1. Introduction

Mosquitoes, *Aedes, Culex* and *Anopheles* sp., are the global vectors of public health importance. These are widely distributed throughout the world and are responsible for transmitting several diseases of human concern such as dengue, Chikungunya, Zika, Malaria, encephalitis and yellow fever, etc. The continuous rise in these diseases has created a worldwide concern. According to the World Health Organization [1], an estimated 241 million global cases of malaria were recorded in 2020 in comparison to the 227 million cases in 2019. Among these, India accounts for 3% of global malaria cases and 2% of malaria deaths across the globe [2]. Likewise, dengue cases have increased intensely leading to about 50% global population at risk of dengue transmission and approximately 100–400 million annual infections [3].

Aedes is a known vector of dengue, Chikungunya, Yellow fever and Zika. According to the reports, the most common urban species, *Ae. aegypti*, was originated as *Ae. aegypti formosus* in the wilds of Sub-Saharan Africa and gradually established globally, more specifically in the tropical and subtropical regions of the world [4–6]. Likewise, *Ae. albopictus,* the peri-urban and rural vector, a native zoophilic species of Southeast Asia, Western Pacific and islands of Indian Ocean, has expanded globally *via* human activities and active transportations [7–9]. It is believed that *Aedes* could spread and establish into new regions because of climatic changes, elevated carbon emissions and global warming leading to the global appearance and expansion of several *Aedes*-borne arboviral diseases [10–12]. *Aedes* is currently distributed throughout the tropics including Africa (from where it originates) and a number of subtropical regions such as South-Eastern United States, the Middle East, Southeast Asia, the Pacific and Indian Islands, and Northern Australia (**Figure 1**).

Among *Culex*, the *Cx. pipiens* is the most widely distributed species responsible for the transmission of encephalitis, West Nile Fever, St. Louis encephalitis, etc. The *Cx. pipiens pipiens*, an old word taxon, is prevalent in temperate regions dispersed from Northern Europe to the highlands of South Africa while *Cx. p. pallens* is distributed throughout temperate Asia and *Cx. p. fatigans* is prevalent in the tropical regions. Another common species, *Cx. quinquefasciatus* is present throughout the tropical and warm temperate regions (**Figure 2**). Presumed to be the native of lowlands of West Africa, it has spread to the New World *via* slave ships dispersing gradually to Asia and other tropical and temperate parts of the world [14].

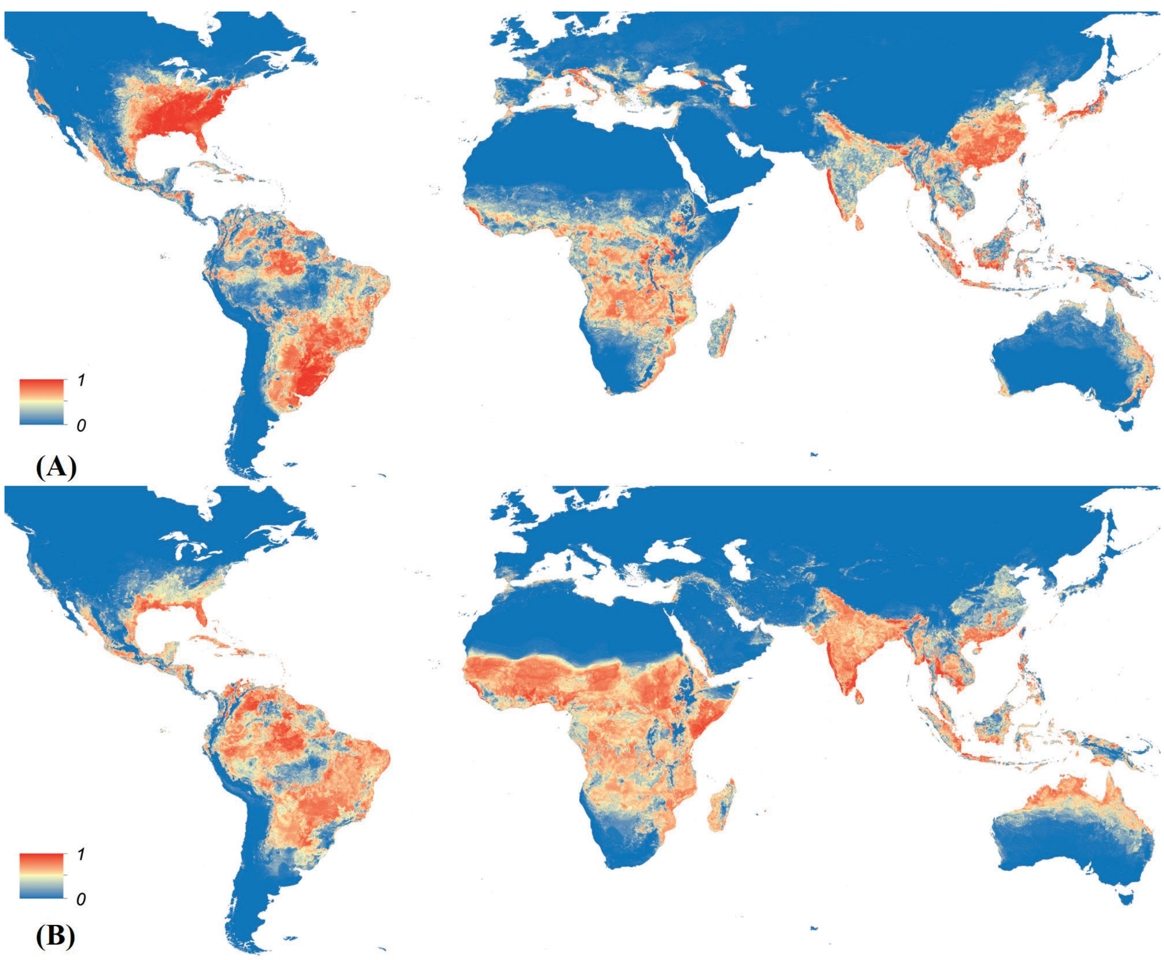

Figure 1.
Predicted distribution of Aedes aegypti (A) and Aedes albopictus (B) [6] (CC-BY-4.0).

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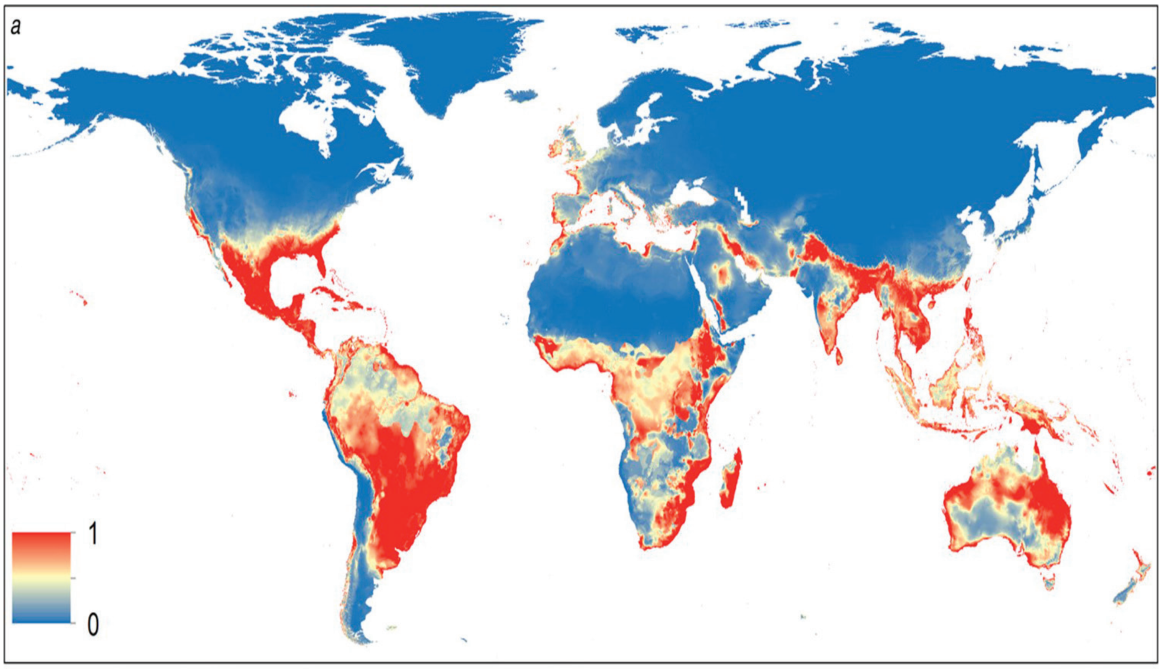

Figure 2.
Global distribution of Culex quinquefasciatus. Red areas represent the most suitable areas, yellow areas as potentially suitable while blue areas as unsuitable areas [13] (CC-BY-4.0).

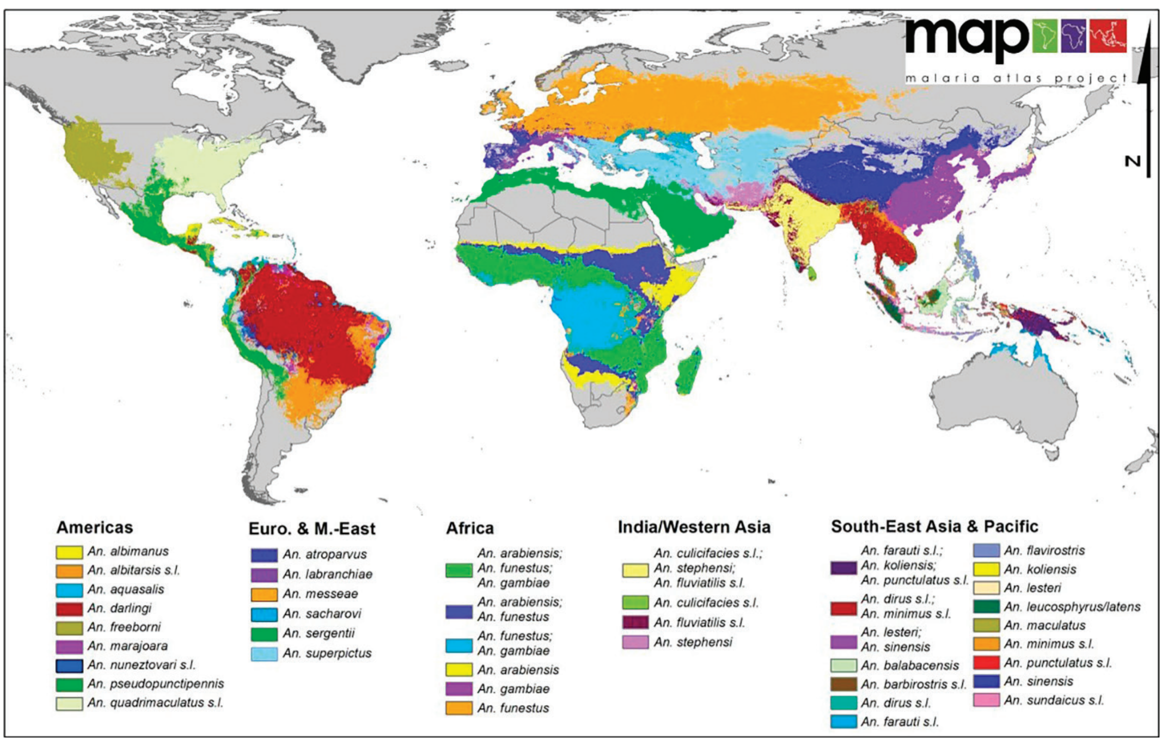

Figure 3.
Global distribution of Anopheles mosquito [15] (CC-BY-2.0).

Like other mosquito vectors, *Anopheles* species is also extensively distributed throughout the world, specifically in the tropical areas though with variability in the complexity (**Figure 3**). In Africa, the hardest hit, *An. gambiae, An. arabiensis* and *An. funestus* are the most common species, whereas in Indian region, *An. culicifacies, An. stephensi* and *An. fluviatilis* are the most prevalent. **Figure 4** depicts the status of

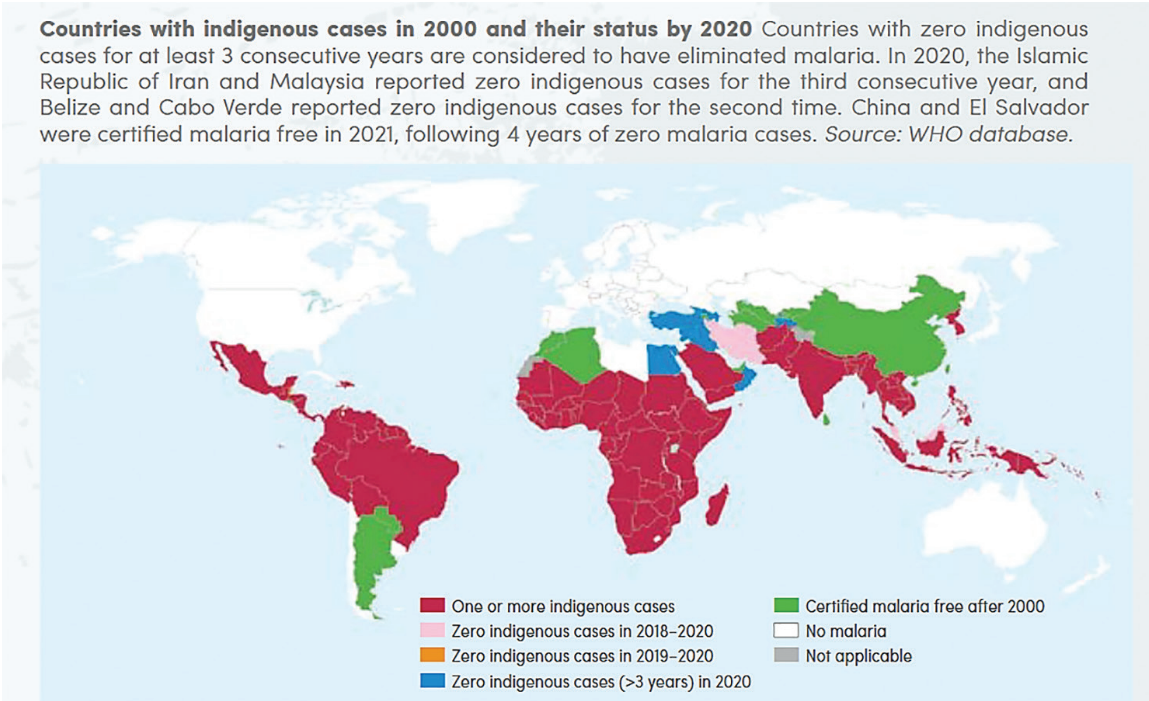

Figure 4.
Indigenous case status of malaria in 2020 [16].

malaria cases in these regions. China and El Salvador were declared malaria-free in 2021 by WHO as no malaria cases were reported in these countries for 4 consecutive years [16]. In addition, Islamic Republic of Iran and Malaysia have been reported to eliminate malaria with zero indigenous cases for 3 consecutive years (**Figure 4**).

2. Management of mosquitoes: Conventional strategies

Management of mosquito-borne diseases largely relies on the vector management because of the lack of effective medication and vaccination. Though, a few vaccines; such as dengvaxia is approved in some countries against dengue fever, 17D against yellow fever and RTS, S/AS01 against malaria; the use of these vaccines is associated with some constraints. For example, dengvaxia is considered effective only for 9–16 years old children and only when they have been previously infected with dengue and are living in areas where dengue is common [17]. Similarly, the WHO has endorsed RTS, S/AS01 vaccine against malaria but just for children and in regions with moderate to high *P. falciparum* malaria transmission [18].

Since olden times, several conventional strategies have been used to control mosquito vectors. Measures such as elimination of mosquito breeding sites and use of net screens on windows and doors to prevent entry of mosquitoes, etc. were commonly employed. During nineteenth century, the progress in science led to the formulation of DDT (an organochlorine) which was used as Indoor Residual Spray (IRS) during the Global Malaria Eradication Campaign (1955–1969) [19]. Gradually, other conventional synthetic insecticides – organophosphates, carbamates, pyrethroids; and Insect growth regulators, like JH analogues – Methoprene, Fenoxycarb, etc.; Chitin Synthesis Inhibitors – Dimiln, Penfluron, etc., were formulated which changed the direction of mosquito control [20]. These chemicals were used as active ingredients in the form of various formulations, sprays, dust, granules, and in mosquito repellents and bed nets, etc.

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These interventions, devised for mosquito management, can be categorized into environmental interferences, chemical-based approaches, and biological control methods. Environmental management strategies include - sanitation, elimination of the mosquito breeding sites, avoid water stagnation, emptying water containers, covering all water-filled containers and waste management. Chemical interventions are based on the use of insecticides such as Temephos, Malathion and pyrethroids. Biological methods use agents such as copepods, larvivorous fish, *Bacillus sphaericus*, dragon fly naiads, may fly naiads, etc. A few measures to control *Aedes*-borne arboviral transmission have been depicted in **Figure 5**.

The use of insecticide-treated door curtains and bed nets (ITN), residual sprays in peri-domestic spaces, indoor residual spraying (IRS) and the control of larval breeding by Temephos and diflubenzuron, etc. are other commonly used approaches for mosquito management. In fact, use of IRS, ITNs (Insecticide-treated Nets) and LLINs (Long Lasting Insecticide-treated Nets) could reduce the malaria incidence in 21st century. Consequently, mass campaigns were held to distribute LLINs in countries with disease epidemics. However, the associated constrains; primarily development of insecticide resistance in mosquitoes and involved operational costs; limit the effectiveness of these approaches. Thus, efforts have been made to impregnate nets with synergized insecticides in order to reduce or reverse the resistance. Nevertheless. despite all efforts, the mosquito-borne diseases are continuing to rise in the world causing illness and morbidities at the global level.

Currently, majority of the mosquito control strategies are reliant on chemical-based interventions. However, use of these toxicants frequently and extensively has increased the problem of environmental pollution and led to widespread development of insecticide resistance in disease vectors. In addition, bioaccumulation of these chemicals in the environment has caused their biological magnification through the ecosystem. It is hypothesized that the vector control can be achieved fast with the implementation of new vector control interventions which can complement long-lasting insecticidal nets and indoor residual spraying. Thus, these issues have highlighted and necessitated the need to manage resistance, prevent resurgence of mosquito-borne diseases and maintain the drive towards disease elimination using biorational, effective and other novel approaches.

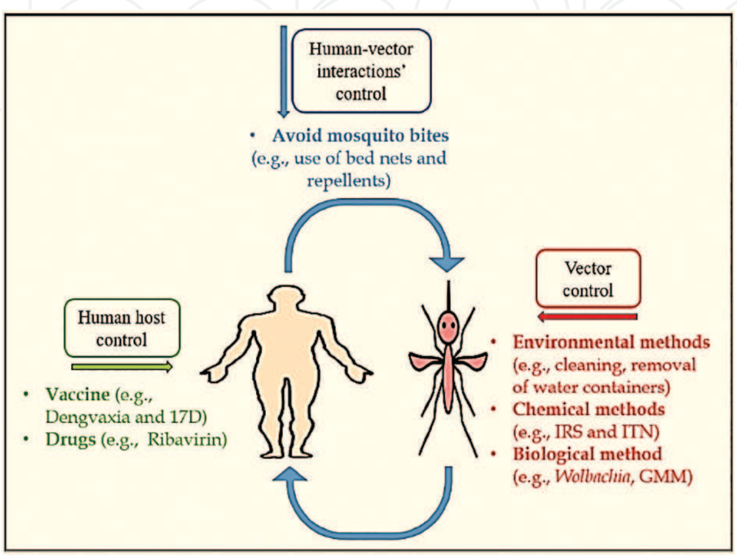

Figure 5.
Measures to control Aedes-borne arboviral transmission [21] (CC-BY-4.0).

3. Management of mosquitoes: Novel strategies

Successful control of mosquitoes requires a comprehensive approach. Since last few decades, several innovative mosquito control interventions and management approaches have been devised including genetic, physical and behavioral approaches. A brief and systematic review of these interventions has been discussed below.

3.1 Sterile insect technique

The use of sterile insects for insect pest management was first described in 1950's by E. F. Knipling. Though this innovative idea of paradigm shift in control interventions was initially used to eradicate screwworm flies, fruit flies etc., the use of SIT approach against mosquitoes has been conceived recently.

The SIT is a 4-step approach: mass production of mosquitoes, sorting males from females, irradiate male mosquitoes to make them sterile and mass release of sterile male mosquitoes into the target area (**Figure 6**). The objective behind the approach is that once released, sterile male mosquitoes compete with the wild males to mate with wild females. As SIT males are sterile, the mating does not produce any offspring and over time, the number of the targeted mosquito species in the area is reduced. The uniqueness of the SIT is that as the pest population reduces, the efficacy of the approach increases. Consequently, continued release of sterile mosquitoes reduces the vector population gradually over generations. Nonetheless, the approach can be successful in isolated population of mosquitoes and when the released male SIT mosquitoes are more numerous than the wild males.

The earlier attempts, however, had mixed success because it was highly problematic to rear and produce enough number of sterile males to suppress natural populations [23]. Further, sex separation in mosquitoes has been formerly based on the mechanical sorting according to the size dimorphism between male and female pupae

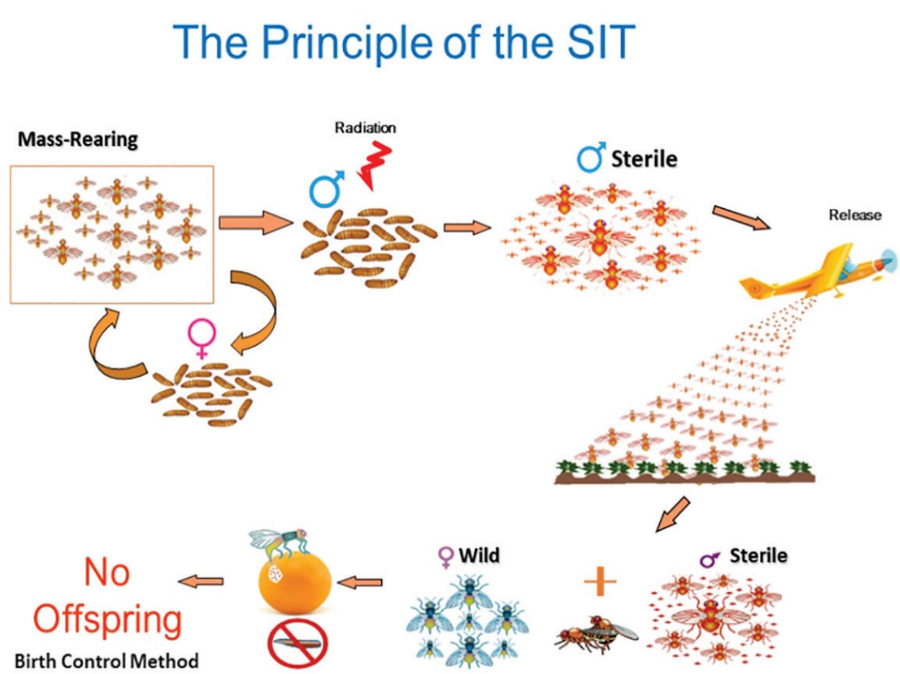

Figure 6.
Principle of sterile insect technique [22] (CC-BY-4.0).

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as according to the reports, the pupal size-based sex separation could consistently give an essentially male-only population [24]. Nevertheless, irradiation at pupal stage used to often damage the insects in comparison to the irradiation at the adult stage which was, but, operationally much more difficult [25].

As a result, now, novel transgenic approaches have been created which help to develop and release required number of mosquitoes in the fields. Such approaches have been used for *An. gambiae* [26], *Ae. aegypti* [27], and *Ae. albopictus* [28]. Using these techniques, transgenic sterile *Ae. aegypti* have been released in the Grand Cayman and have demonstrated an effective reduction of these mosquitoes [29].

It is recommended that novel genetic methods using sex-linked markers may enhance the accuracy and efficiency of sex-sorting. For instance, the specificity of the homing endonuclease I-PpoI (Intron encoded endonuclease) of *An. gambiae* was exploited to distort sex ratio by producing only male offspring. The endonuclease selectively cleaved the ribosomal gene sequences located on the X chromosome (**Figure 7**). Slicing of the X chromosome prevents its transmission to the next generation and produced >95% male offspring [26].

The SIT technique is often used as a complement to other approaches as it is ecologically benign and insect-specific. The major limitation of SIT is that it is non-persistent in the environment because of inability of SIT mosquitoes to reproduce. Thus, once the release of these mosquitoes is stopped, the targeted mosquito species can return to normal. Hence, the technique demands regular release of irradiated males to be successful. Other constraints include – heavy expenditure to set up rearing and irradiation facility, complications in segregation of male mosquitoes, transportation issues, probable overdose of radiation which might affect vitals, and release of mosquitoes in isolated areas to avoid immigration of wild males and gravid females. The approach requires planning and commitment for long-term implementation due to its slow action as unlike fast-acting chemical interventions with immediate actions, it compromises the hereditary machinery of insect pest population by affecting next generation.

3.2 Release of insects carrying a dominant lethal (RIDL)

The limitations and issues associated with SIT could also be alleviated by the use of transgenic strains carrying specific novel traits, such as conditional genetic sterilization or lethality. The approach is based on the concept that transgenic strains of mosquitoes carrying a female-specific lethal gene could be used to remove females prior to release in the fields. It will remove the need for irradiation of males to manage vector population.

The RIDL approach acts late in the development and thus, it prevents mosquitoes from becoming adults. It was reported that introduction of LA 513 transposons into the mosquito's DNA produced offspring that die in the larval stage. The approach has been recommended in Malaysia as a control measure of *Ae. aegypti* [30].

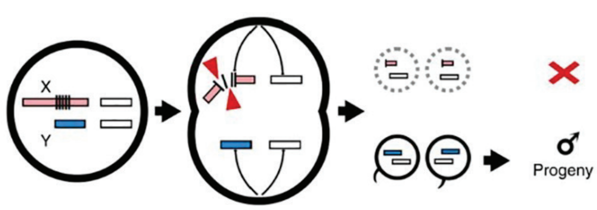

Figure 7.
Distortion of the sex ratio model in mosquitoes towards males based on meiotic X shredding [26] (CC-BY-NC-SA-3.0).

In another study, the “flightless female” *Ae. aegypti* has been developed by the genetic engineering of synthetic phenotypes [31]. The gene present in the strain encodes a toxin which destroys the wing muscles of females because of which the they are unable to fly, mate or search their food and oviposition sites. In *Ae. albopictus,* the gene *Actin-4* has been isolated to drive a dominant lethal gene in the indirect flight muscles leading to the development of a conditional female-specific flightless phenotype [28].

3.3 Male determining factor

The scientific advancement has discovered the male determining factor (M factor) in mosquitoes located within a Y chromosome–like highly repetitive M locus. These include *Nix* in *Ae. aegypti* [32], *gYG2/Yob* in *An. gambiae* [33, 34] and *Guy1* in *An. stephensi* [35]. A dominant male-determining locus (M-locus) establishes the male sex (M/m) in the yellow fever mosquito, *Ae. aegypti*.

It was discovered that knocking out the *Nix* gene results in feminized males while ectopic expression gave masculinized females with male genitalia [32]. Demonstration that M locus determines the male sex in *Ae. aegypti* and is thus inherited by only male mosquitoes has been carried out [36]. In case, the *Nix* gene inserted into a chromosomal region is inherited by the female *Ae. aegypti*, the mosquitoes can convert into non-biting males. They recommended that female-to-male sex conversion by *Nix* can complement SIT that requires only non-biting males and can help in reducing vector population to a great extent.

A *myo-sex* gene, need for flight, has also been discovered in the M-locus of male *Ae. aegypti* [36]. They demonstrated that the non-biting males converted from females lack this gene and thus were unable to fly for mating. They could not fold their wings completely but could walk and sometimes jump.

3.4 *Wolbachia*-based control

Wolbachia, an intracellular bacterium, is found in more than 50% of insect species and is transmitted vertically [37]. Mosquitoes do not possess *Wolbachia* but it can be introduced in the mosquito through trans-infections. The first *Wolbachia* strain (*wPip - Wolbachia pipientis*) was discovered in *Cx. pipiens* [38]. Later, other strains, *wAlbA* and *wAlbB* were found in *Ae. albopictus* [39].

The bacterium has been used to manage mosquito population, especially *Aedes.* It is reported that *Wolbachia*-based control techniques can not only disrupt replication and transmission of arbovirus; but the bacterium can also suppress the vector population [40]. *Wolbachia*-based mosquito control strategy involves two kinds of approaches – either replacement or suppression of the population [41]. In the population replacement strategy, the female mosquitoes infected with *Wolbachia* are released in the fields. The offspring of these mosquitoes are viable, whether they mate with *Wolbachia*-infected males or uninfected males. This allows the spread of *Wolbachia* in the field population. Consequently, though the total number of mosquitoes remains unchanged the individuals are less competent (**Figure 8**). On the other hand, in population suppression strategy, *Wolbachia*-infected males are released in the fields. These, when mate with the wild females, do not produce viable offspring. Thus, this strategy reduces the total number of mosquitoes instead of affecting their competency (**Figure 8**).

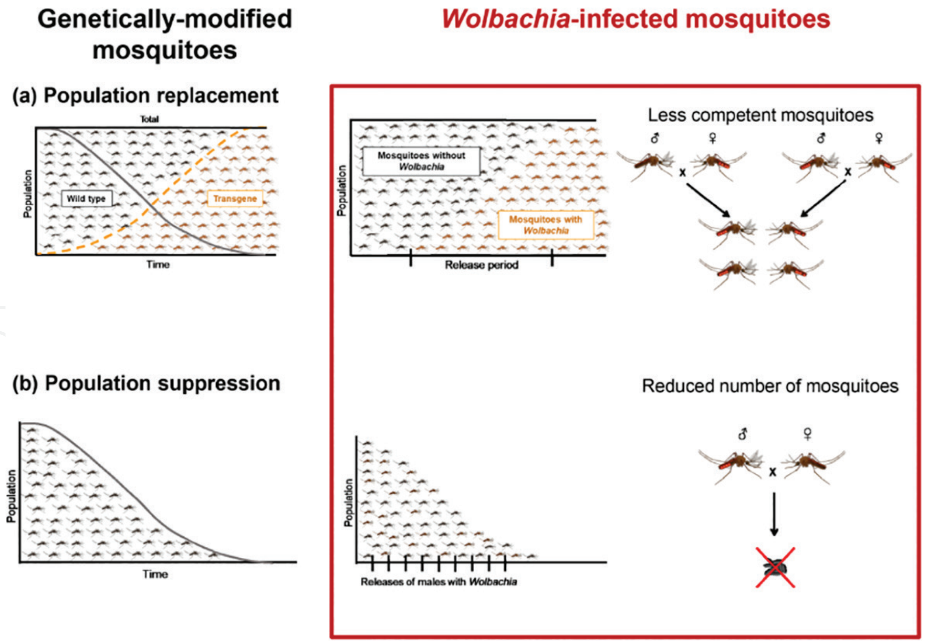

Figure 8.
Wolbachia-based mosquito control strategy [41] (CC-BY-4.0).

The studies have revealed that the *Wolbachia* trans-infection may decrease the fitness of *Aedes* leading to the population reduction and could halve its life-span [42, 43]. The study also showed that the mortality in *Wolbachia*-infected (*wMel, wAlbB, wMelPop*) mosquitoes was significantly higher in comparison to their wilds counterparts. In northern Australia, a *w*AlbB2-F4 strain has been generated which showed incompatibility with the wild strain as well as *w*Mel-*Wolbachia Ae. aegypti* [44]. The strain was mass reared and sexes were sorted in order to release only males in the field. They released 3 million males in 600 houses, approximately 50 males/house, 3 times a week for 20 weeks and recorded 80% decline in population in comparison to the control.

Research has shown that *Wolbachia*-infected strains have a competitive benefit over their wild counterparts. Mating between *Wolbachia*-infected male *Ae. aegypti* and wild female mosquitoes results in sterile eggs due to unidirectional cytoplasmic incompatibility [45]. In addition, the mating between male and female infected with different *Wolbachia* strains could also produce non-viable offspring (bidirectional incompatibility) [46]. Hence, in SIT, if *Wolbachia*-infected males are used and released regularly, the vector population can reduce drastically.

In addition, the *Wolbachia* has the capacity to block the transmission of dengue and Zika viruses by *Aedes* species. Studies have suggested that *Wolbachia*-infected *Ae. aegypti* might fix in the target population [47, 48]. In Kuala Lumpur, Malaysia, by 18 months of *Wolbachia*-host coevolution in the field, it was observed that blocking of dengue virus transmission and unidirectional cytoplasmic incompatibility were not compromised in a field-adapted *wAlbB*-carrying *Ae. aegypti* strain [49]. Thus, *Wolbachia*-based control can be three-pronged approach; release of *Wolbachia*-infected male mosquitoes along with uninfected female mosquitoes resulting in sterile offspring due to CI; introduction of *Wolbachia* strain causing fitness cost by reducing the life-span; and invasion of *Wolbachia* strain that inhibits virus transmission (**Figure 9**).

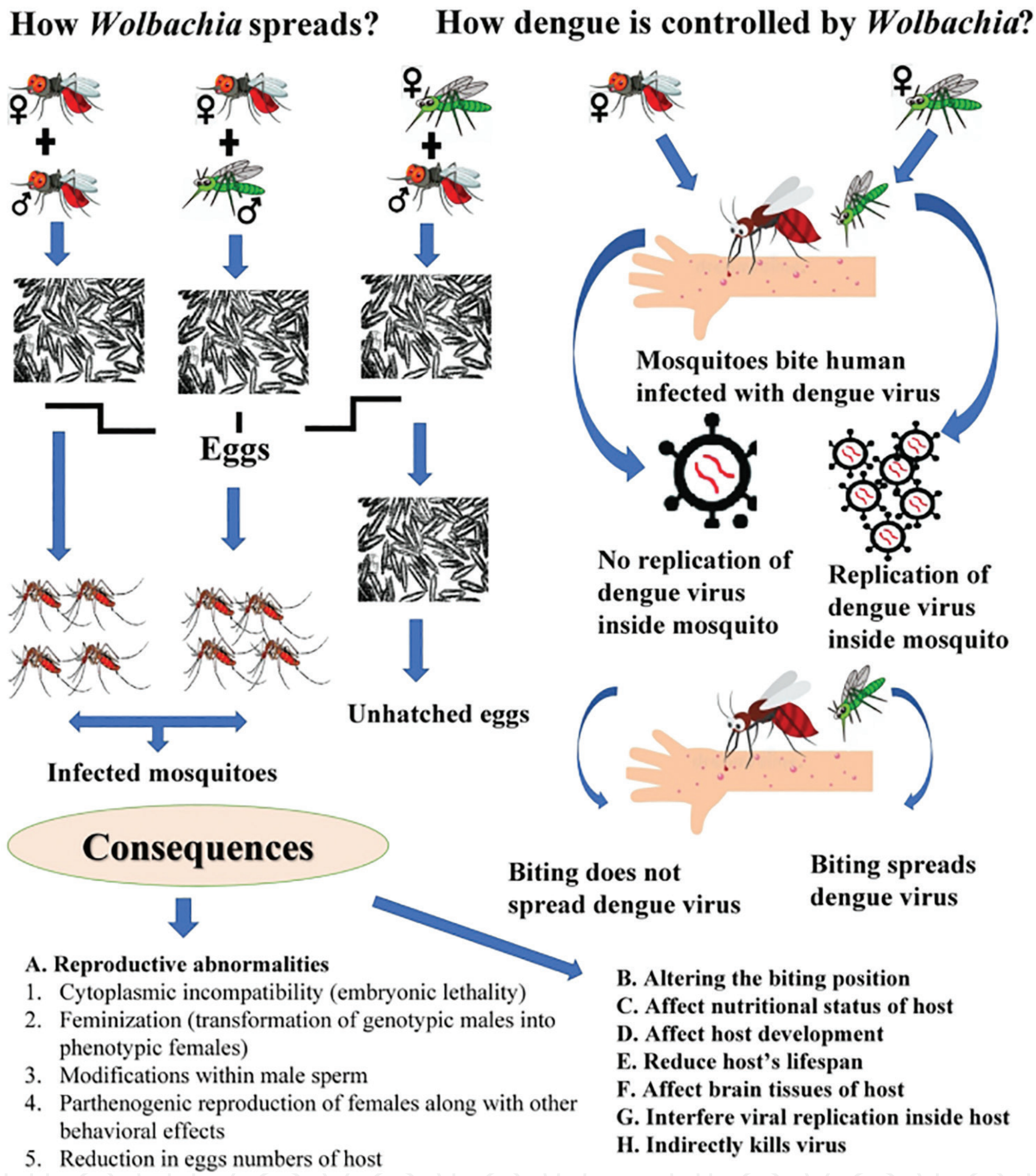

Figure 9.
Vertical transmission of Wolbachia and its role in reducing fitness of Aedes sp. and inhibition of dengue virus transmission. Red colored mosquitoes are infected with Wolbachia while green colored mosquitoes are uninfected [50] (CC-BY-4.0).

3.5 Gene drive

CRISPR-based gene drives are selfish genetic elements that can be used to modify entire populations of the mosquito for sustainable vector control [51]. Using gene drive technology, a genetic modification can spread through a population at higher inheritance rates than the normal. These technologies have been investigated in *An. gambiae, An. stephensi* and other mosquito species. The approach can either suppress a wild mosquito population or reduce its transmission competency by spreading genes that interfere with parasite development.

A highly effective and autonomous CRISPR-associated protein 9 (Cas9)-mediated gene-drive system has been developed in *An. stephensi* which resulted in progeny derived from transgenic males exhibiting a high frequency of germ-line gene conversion [52]. Earlier, it was used in *An. gambiae* for knocking out the genes responsible for female fertility exhibiting the potential to pass through consecutive generations [53].

3.6 Attractive toxic sugar bait (ATSB)

Attractive-toxic sugar baits are considered a new vector control paradigm based on "attract and kill" approach. The approach is based on the natural behavior of the mosquitoes to feed on plant sugars as an energy source immediately after emergence and intermittently during their life history. It is a known fact that the successful feeding by mosquito adults helps in high survival rate and reproductive fitness of mosquito. Though it is an old-age known fact, yet this behavior of mosquitoes was not tapped till recent times. Nowadays, the sugar feeding behavior of mosquito is being tapped to formulate ATSBs by combining a concentrated sugar-based food source, an olfaction stimulant to lure mosquitoes and a systemic insecticide to kill them. It is believed that development of ATSBs may contribute to their localized control.

ATSB approach has been favored as mosquito control strategy since use of a safe systemic toxin, such as boric acid, targets the sugar-seeking behavior of mosquitoes and can evade problems conventionally associated with the indiscriminate use of contact insecticides [54]. This method is suitable to be combined with any type of low-risk gut toxin, which makes it a potential and plausible tool to fight rising resistance against conventional contact pesticides [55].

Application of mosquito sugar-feeding behavior as a control strategy was first observed successfully in *Ae. aegypti* adults which when fed upon a paper incorporated with malathion-sugar solution exhibited 85.2% mortality [56]. Likewise, *Bacillus sphaericus* spores incorporated with the sucrose/dye solutions resulted in effective mortality in *Cx. pipiens* [57]. Now, researchers are exploring diverse toxic sugar baits containing fruit or flower juice as an attractant and different types and concentrations of toxic active ingredients against mosquito vectors.

The aim of using the attractant in the formulation is to manipulate mosquito behavior moving them away from their natural sugar sources, attracting towards bait and encourage feeding. The baits can be applied to the foliage, or kept in a simple trap, such as plastic bottles (bait stations) to lure and kill, capitalizing on resting and sugar seeking mosquitoes. The approach offers an exceptional tool of pesticide delivery. The concentrated sugar source prompts a natural feeding response in mosquitoes. The mosquitoes, then ingest the bait and receive the active toxic ingredients integrated with the bait [58]. The researchers are attempting to use contact insecticides too along with which can enter the mosquito body during their visit to the bait.

As mosquitoes spend most of their time in particular outdoor microhabitats, there is a high probability that mosquitoes ingest ATSB solution at their resting sites. Application of a dyed sucrose-spinosad solution on the tree flowers at desert areas had resulted in a substantial reduction in the feral mosquitoes as compared to that at the control locations [59]. The ATSB trials were held against *An. sergentii* and *An. gambiae* in an arid habitat of Israel with relatively little sugar source vegetation which proved to be highly successful [60]. The approach resulted in over 98% reduction in the sugar-poor sites. Interestingly, over 95% population reduced even in the sugar-rich sites. Likewise, a dramatic reduction of daily survival rates and malaria vectorial capacity was observed in *An. gambiae,* from 11.2 to 0.0 in sugar-poor sites and from 79.0 to 0.3 in sugar-rich sites. Similarly, about 90% of mosquitoes emerged from cisterns and wells were found to feed on ASB which suggested that applications of ATSB could be successful in storm drain systems [61].

A few successful ATSB field trials have also controlled *Cx. quinquefasciatus* from storm drains in Florida, USA and *An. gambiae* in Mali, West Africa reducing the population by 90% [62]. The ATSB treatments in Mali also reduced the longevity of older mosquitoes which had completed three or more gonotrophic cycles and decreased the mosquito prevalence from 37% pre-treatment to 6% post treatment in a month's time [63].

Application of a TSB containing 5% sucrose solution and 1% boric acid in the habitat of *Ae. taeniorhynchus* larvae could significantly reduce the landing rate counts of adults [64]. The application of 0.4% microencapsulated garlic-oil to local vegetation as the oral toxin component of ATSB for controlling *An. sergentii* populations inhabiting desert-surrounded wetlands in Israel reduced the biting-pressure by 97.5% [65]. Different juices and bait prototypes were investigated in laboratory and field-simulated conditions to control *An. arabiensis* [66]. The preference of mosquitoes was found for orange, watermelon and commercial guava juice over tomato, mango and banana. The results elucidated that the design of the sugar bait can influence feeding rates and, therefore, efficacy. Sugar baits that offered a resting surface were found more efficient and feeding on the sugar baits was maximized when these were placed close to peri-domestic vegetation.

In a laboratory study, 48 h exposure of *Ae. albopictus*, *Ae. taeniorhynchus* and *Cx. nigripalpus* to the non-flowering *Rhaphiolepis indica* (L.) plants sprayed with TSB containing 5% sucrose solution and 1% boric acid resulted in >96% mortality in all mosquito species [67]. Sugar baits formulated with boric acid, deltamethrin and dinotefuran tested against *Cx. quinquefasciatus* showed higher efficacy of boric acid and dinotefuran baits against resistant populations while that of deltamethrin bait against susceptible population [68]. The carbamate-resistant strain of *Cx. quinquefasciatus* has also been found significantly more affected by dinotefuran than the susceptible strain suggesting that toxicity of dinotefuran against mosquitoes is not strongly affected by the presence of common resistance mechanism, i.e., *kdr* mutation and insensitive acetylcholinesterase [69]. Indoor trials conducted with ATSB bait station, containing guava juice-bait mixed with chlorfenapyr (0.5%), boric acid (2%), oxazolamide (1%) in experimental huts (**Figure 10**) as well as window traps (**Figure 11**), could also

Figure 10.
ATSB station positioning in experimental huts [70] (CC-BY-4.0).

Figure 11.
ATSB station positioning near windows [70] (CC-BY-4.0).

successfully attract and kill *Cx. quinquefasciatus [70]*. Use of aqueous sugar solutions in bait stations containing boric acid, fipronil, or spinosad resulted in significant reductions of local mosquito populations [59, 71].

Nevertheless, the selection of the toxicant to be included in an ATSB has remained a scientific concern as non-target species may be affected and also children may be attracted given the sweet nature of the substrate [72]. A comprehensive review of the advancements in the attractive toxic sugar baits for the mosquito control has highlighted their effects on the mosquito larvae and non-target insects, as well as has discussed future applications of ATSB methodologies [73]. The possible efficacy of TSBs and ATSBs in mosquito management recommends their integration into mosquito abatement programs.

3.7 Optical approaches

Various physical management strategies have been devised which use devices, such as microphones, sensors, lasers and light detectors to identify mosquitoes and detect, monitor, and investigate their behavior. The method aims to reduce energy consumption, and enhance trapping and killing of specific insects.

Lowell Wood, an astrophysicist invented a laser-based device to kill mosquitoes. The "Mosquito Laser" uses an imaging CCD Camera along with a LED and a retroflective material to detect mosquitoes. A high-power laser is then released on the detected target which kills it by physical disintegration. It is a very novel technique which is still in the prototype stage. However, this approach can be dangerous for humans as well as the environment.

The short (<25 ms) laser pulses have been used to kill/disable *An. stephensi* females (**Figure 12**). The researchers reported the higher efficacy of green and far-infrared

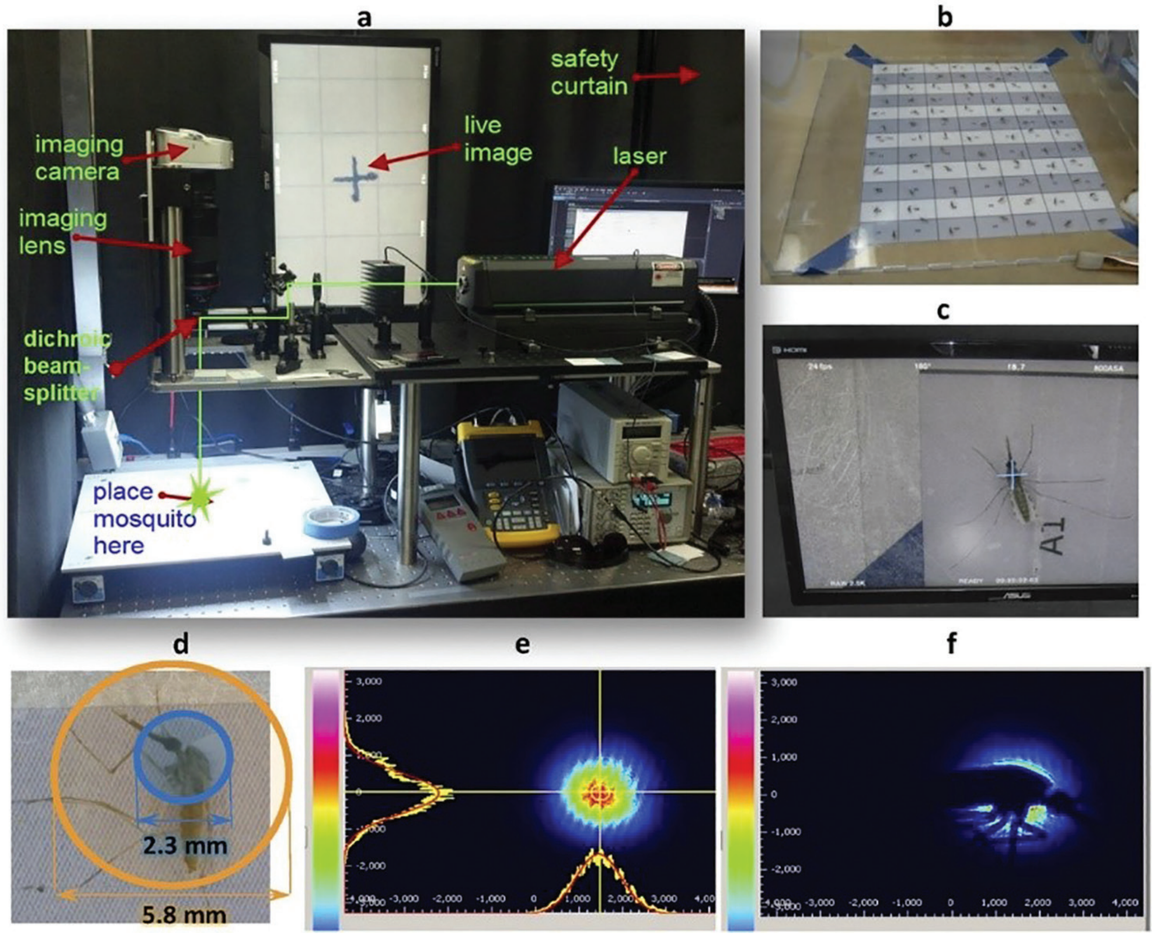

Figure 12.
Laser-induced killing of Anopheles stephensi (a) the current dosing laser co-aligned axially with an imaging camera; (b) anesthetized mosquitoes arranged in a 12 by 7 grid (c) view from the camera; (d) areas hit by the two typical beam diameters indicated by the circles; (e, f) Images from CCD beam (e) without and (f) with a subject [74] (CC-BY-4.0).

wavelengths in comparison to near- and mid-infrared wavelengths [74]. They recommended the use of cheap, robust lasers with sufficient beam quality so that they can be focused over a long range to kill mosquitoes. Earlier, efficacy of low power blue light to disable mosquitoes has been shown on exposure for several hours to days [75].

4. Conclusions

Prevention and control of mosquito-borne diseases, currently rely on the vector control due to the lack of effective medication and vaccines. The mosquito control has become a global challenge due to its widespread occurrence and transmission of diseases at a rapid rate. Despite the use of diverse conventional strategies; chemicals-based interventions, environmental management, human-vector interaction control, use of biological agents, etc.; the world is facing continual rise in these diseases. Thus, there is a need for the adequate implementation of these control strategies. Presently, mosquito control is based on the use of chemical insecticides. However, the recurrent and unsystematic use of these toxicants have caused harm to the human health, non-targets and the environment. Hence, researchers are incessantly exploring the alternate innovative strategies. The interventions which are covered in this Chapter can supplement the existing strategies and help to alleviate the mosquito population. Nevertheless, implementation of any new measure requires monitoring of its success which itself is a logistic challenge. It is recommended to carry out regular mosquito surveillance in the prevalent areas and implement the integrated mosquito control strategy.

Conflict of interest

The authors declare no conflict of interest.

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References

[1] World Health Organization (WHO). Malaria. 2022a. Available from: https://www.who.int/news-room/fact-sheets/detail/malaria [Accessed: May 10, 2022]

[2] World Malaria Report. 2019. https://www.who.int/publications/i/item/9789241565721 [Accessed: May 2, 2022]

[3] World Health Organization (WHO). Dengue and Severe Dengue. 2022b. Available from: https://www.who.int/news-room/fact-sheets/detail/dengue-and-severe-dengue [Accessed: May 10, 2022]

[4] Brown JE, McBride CS, Johnson P, Ritchie S, Paupy C, Bossin H, et al. Worldwide patterns of genetic differentiation imply 'domestications' of *Aedes aegypti*, a major vector of human diseases. Proceedings of the Royal Society B: Biological Sciences. 2011;**278**(1717):2446-2454. DOI: 10.1098/rspb.2010.2469

[5] Brown JE, Evans BR, Zheng W, Obas V, Barrera-Martinez L, Egizi A, et al. Human impacts have shaped historical and recent evolution in *Aedes aegypti*, the dengue and yellow fever mosquito. Evolution. 2014;**68**(2):514-525. DOI: 10.1111/evo.12281

[6] Kraemer MU, Sinka ME, Duda KA, Mylne AQ, Shearer FM, Barker CM, et al. The global distribution of the arbovirus vectors *Aedes aegypti* and *Ae. albopictus*. eLife. 2015;**4**:e08347. DOI: 10.7554/eLife.08347

[7] Ponlawat A, Harrington LC. Blood feeding patterns of *Aedes aegypti* and *Aedes albopictus* in Thailand. Journal of Medical Entomology. 2005;**42**(5):844-849. DOI: 10.1093/jmedent/42.5.844

[8] Delatte H, Gimonneau G, Triboire A, Fontenille D. Influence of temperature on immature development, survival, longevity, fecundity, and gonotrophic cycles of *Aedes albopictus*, vector of chikungunya and dengue in the Indian Ocean. Journal of Medical Entomology. 2009;**46**(1):33-41. DOI: 10.1603/033.046.0105

[9] Izri A, Bitam I, Charrel RN. First entomological documentation of *Aedes* (*Stegomyia*) *albopictus* (Skuse, 1894) in Algeria. Clinical Microbiology and Infection. 2011;**17**(7):1116-1118. DOI: 10.1111/j.1469-0691.2010.03443.x

[10] Carrington LB, Simmons CP. Human to mosquito transmission of dengue viruses. Frontiers in Immunology. 2014;**5**:290. DOI: 10.3389/fimmu.2014.00290

[11] Semenza JC, Sudre B, Miniota J, Rossi M, Hu W, Kossowsky D, et al. International dispersal of dengue through air travel: Importation risk for Europe. PLoS Neglected Tropical Diseases. 2014;**8**(12):e3278. DOI: 10.1371/journal.pntd.0003278

[12] Messina JP, Brady OJ, Pigott DM, Golding N, Kraemer MU, Scott TW, et al. The many projected futures of dengue. Nature Reviews Microbiology. 2015;**13**(4):230-239. DOI: 10.1038/nrmicro3430

[13] Alaniz AJ, Carvajal MA, Bacigalupo A, Cattan PE. Global spatial assessment of *Aedes aegypti* and *Culex quinquefasciatus*: A scenario of Zika virus exposure. Epidemiology and Infection. 2019;**147**:E52. DOI: 10.1017/S0950268818003102

[14] CABI (Centre for Agriculture and Bioscience International). *Culex*

quinquefasciatus (Southern House mosquito). 2012. Available from: https://www.cabi.org/isc/datasheet/86848 [Accessed: May 17, 2022]

[15] Sinka ME, Bangs MJ, Manguin S, Rubio-Palis Y, Chareonviriyaphap T, Coetzee M, et al. A global map of dominant malaria vectors. Parasite & Vectors. 2012;**5**:69. DOI: 10.1186/1756-3305-5-69

[16] World Malaria Report 2021. Available from: https://www.who.int/publications/i/item/9789240040496 [Accessed: February 10, 2022]

[17] Centre for Disease Control and Prevention (CDC). Dengue vaccination: What everyone should Know. 2022. https://www.cdc.gov/vaccines/vpd/dengue/public/index.html [Accessed: May 11, 2022]

[18] World Health Organization (WHO). WHO recommends groundbreaking vaccine for children at risk. 2021. Available from: https://www.who.int/news/item/06-10-2021-who-recommends-groundbreaking-malaria-vaccine-for-children-at-risk [Accessed: May 11, 2022]

[19] Centre for Disease Control and Prevention (CDC). Indoor Residual Spraying. 2019. https://www.cdc.gov/malaria/malaria_worldwide/reduction/irs.html [Accessed: May 11, 2022]

[20] Mamatha DM, Kanji VK, Cohly HH, Rao MR. Juvenile hormone analogues, methoprene and fenoxycarb dose dependently enhance certain enzyme activities in the silkworm *Bombyx mori* (L). International Journal of Environmental Research and Public Health. 2008;**5**(2):120-124. DOI: 10.3390/ijerph5020120

[21] Ogunlade ST, Meehan MT, Adekunle AI, Rojas DP, Adegboye OA, McBryde ES. A review: *Aedes*-borne arboviral infections, controls and *Wolbachia*-based strategies. Vaccine. 2021;**9**(1):32. DOI: 10.3390/vaccines9010032

[22] Vreysen MJB, Abd-Alla AMM, Bourtzis K, Bouyer J, Caceres C, de Beer C, et al. The insect pest control laboratory of the joint FAO/IAEA programme: Ten years (2010-2020) of research and development, achievements and challenges in support of the sterile insect technique. Insects. 2021;**12**:346. DOI: 10.3390/insects12040346

[23] Benedict MQ, Robinson AS. The first releases of transgenic mosquitoes: An argument for the sterile insect technique. Trends in Parasitology. 2003;**19**(8):349-355. DOI: 10.1016/s1471-4922(03)00144-2

[24] Ansari MA, Singh KR, Brooks GD, Malhotra PR, Vaidyanathan V. The development of procedures and techniques for mass rearing of *Aedes aegypti*. Indian Journal of Medical Research. 1977;**65**(Suppl):91-99

[25] Andreasen MH, Curtis CF. Optimal life stage for radiation sterilization of *Anopheles* for sterile insect releases. Medical Veterinary Entomology. 2005;**19**:238-244. DOI: 10.1111/j.1365-2915.2005.00565.x

[26] Galizi R, Doyle L, Menichelli M, Bernardini F, Deredec A, Burt A, et al. A synthetic sex ratio distortion system for the control of the human malaria mosquito. Nature Communications. 2014;**5**:3977. DOI: 10.1038/ncomms4977

[27] Phuc HK, Andreasen MH, Burton RS, Vass C, Epton MJ, Pape G, et al. Late-acting dominant lethal genetic systems and mosquito control. BMC Biology. 2007;**5**:11. DOI: 10.1186/1741-7007-5-11

[28] Labbé GM, Scaife S, Morgan SA, Curtis ZH, Alphey L. Female-specific flightless (fsRIDL) phenotype for control of *Aedes albopictus*. PLoS Neglected Tropical Diseases. 2012;**6**:e1724. DOI: 10.1371/journal.pntd.0001724

[29] 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. Nature Biotechnology. 2012;**30**:828-830

[30] Aldridge S. Genetically modified mosquitoes. Nature Biotechnology. 2008;**26**:828-830

[31] Macias VM, Ohm JR, Rasgon JL. Gene drive for mosquito control: Where did it come from and where are we headed? International Journal of Environmental Research and Public Health. 2017;**14**(9):1006. DOI: 10.3390/ijerph14091006

[32] Hall AB, Basu S, Jiang X, Qi Y, Timoshevskiy VA, Biedler JK, et al. A male-determining factor in the mosquito *Aedes aegypti*. Science. 2015;**348**:1268-1270

[33] Hall AB, Papathanos P-A, Sharma A, Cheng C, Akbari CC, Assour L, et al. Radical remodeling of the Y chromosome in a recent radiation of malaria mosquitoes. Proceedings of National Academy of Sciences USA. 2016;**113**:E2114-E2123. DOI: 10.1073/pnas.1525164113

[34] Krzywinska E, Dennison NJ, Lycett GJ, Krzywinski J. A maleness gene in the malaria mosquito *Anopheles gambiae*. Science. 2016;**353**:67-69. DOI: 10.1126/science.aaf5605

[35] Criscione F, Qi Y, Tu Z. GUY1 confers complete female lethality and is a strong candidate for a male-determining factor in *Anopheles stephensi*. eLife. 2016;**5**:e19281. DOI: 10.7554/eLife.19281

[36] Aryan A, Anderson MAE. Biedler Jk, Qi Y, Overcash JM, Naumenko AN, Sharakhova MV, Mao C, Adelman ZN, Tu Z. *nix* alone is sufficient to convert female *Aedes aegypti* into fertile males and *myo-sex* is needed for male flight. Proceedings of National Academy of Sciences USA. 2020;**117**(30):17702-17709. DOI: 10.1073/pnas.2001132117

[37] Hilgenboecker K, Hammerstein P, Schlattmann P, Telschow A, Werren JH. How many species are infected with *Wolbachia*? – A statistical analysis of current data. FEMS Microbiology Letters. 2008;**281**:215-220. DOI: 10.1111/j.1574-6968.2008.01110.x

[38] Hertig M, Wolbach S. Studies on rickettsia-like micro-organisms in insects. Journal of Medical Research. 1924;**44**:329-374

[39] Zhou W, Rousset F, O'Neill SL. Phylogeny and PCR-based classification of *Wolbachia* strains using *wsp* gene sequences. Proceedings of the Royal Society B: Biological Science. 1998;**265**:509-515. DOI: 10.1098/rspb.1998.0324

[40] Hoffmann AA, Ross PA, Rašić G. *Wolbachia* strains for disease control: Ecological and evolutionary considerations. Evolutionary Applications. 2015;**8**:751-768. DOI: 10.1111/eva.12286

[41] Yen P-S, Failloux A-B. A review: *Wolbachia*-based population replacement for mosquito control shares common points with genetically modified control approaches. Pathogens. 2020;**9**(5):404. DOI: 10.3390/pathogens9050404

[42] McMeniman CJ, Lane RV, Cass BN, Fong AWC, Sidhu M, Wang Y-F, et al. Stable introduction of a life-shortening *Wolbachia* infection into the mosquito *Aedes aegypti*. Science. 2009;**323**:141-144. DOI: 10.1126/science.1165326

[43] Axford JK, Callahan AG, Hoffmann AA, Yeap HL, Ross PA. Fitness of wAlbB *Wolbachia* infection in *Aedes aegypti*: Parameter estimates in an outcrossed background and potential for population invasion. The American Journal of Tropical Medicine and Hygiene. 2016;**94**:507-516. DOI: 10.4269/ajtmh.15-0608

[44] Beebe NW, Pagendam D, Trewin BJ, Bomer A, Bradford M, Ford A, et al. Releasing incompatible males drives strong suppression across populations of wild and *Wolbachia*-carrying *Aedes aegypti* in Australia. Proceedings of National Academy of Sciences USA. 2021;**118**(41):e2106828118. DOI: 10.1073/pnas.2106828118

[45] Flor M, Hammerstein P, Telschow A. *Wolbachia*-induced unidirectional cytoplasmic incompatibility and the stability of infection polymorphism in parapatric host populations. Journal of Evolutionary Biology. 2007;**20**:696-706. DOI: 10.1111/j.1420-9101.2006.01252.x

[46] Zhong Y, Li Z-X. Bidirectional cytoplasmic incompatibility induced by cross-order transfection of *Wolbachia*: Implications for control of the host population. Microbial Ecology. 2014;**68**:463-471. DOI: 10.1007/s00248-014-0425-2

[47] Nazni WA, Hoffmann AA, Noor Afizah A, Cheong YL, Mancini MV, Golding N, et al. Establishment of *Wolbachia* strain wAlbB in Malaysian populations of *Aedes aegypti* for dengue control. Current Biology. 2019;**29**:4241-4248.e5. DOI: 10.1016/j.cub.2019.11.007

[48] Ryan PA, Turley AP, Wilson G, Hurst TP, Retzki K, Brown-Kenyon J, et al. Establishment of wMel *Wolbachia* in *Aedes aegypti* mosquitoes and reduction of local dengue transmission in Cairns and surrounding locations in northern Queensland, Australia. Gates Open Research. 2020;**3**:1547. DOI: 10.12688/gatesopenres.13061.2

[49] Ahmad NA, Mancini M-V, Ant TH, Martinez J, Kamarul GMR, Nazni WA, et al. *Wolbachia* strain wAlbB maintains high density and dengue inhibition following introduction into a field population of *Aedes aegypti*. Philosophical Transactions of the Royal Society B. 2021;**376**:20190809. DOI: 10.1098/rstb.2019.0809

[50] Khadka S, Proshad R, Thapa A, Acharya KP, Kormoker T. *Wolbachia*: A possible weapon for controlling dengue in Nepal. Tropical Medicine and Health. 2020;**48**:50. DOI: 10.1186/s41182-020-00237-4

[51] Hammond A, Pollegioni P, Persampieri T, North A, Minuz R, Trusso A, et al. Gene-drive suppression of mosquito populations in large cages as a bridge between lab and field. Nature Communications. 2021;**12**:4589. DOI: 10.1038/s41467-021-24790-6

[52] Gantz VM, Jasinskiene N, Tatarenkova O, Fazekas A, Macias VM, Bier E, et al. Highly efficient Cas9-mediated gene drive for population modification of the malaria vector mosquito *Anopheles stephensi*. Proceedings of National Academy of Sciences USA. 2015;**112**(49):E6736-E6743. DOI: 10.1073/pnas.1521077112

[53] Hammond A, Galizi R, Kyrou K, Simoni A, Siniscalchi C, Katsanos D, et al. A CRISPR-Cas9 gene drive system targeting female reproduction in the malaria mosquito vector *Anopheles gambiae*. Nature Biotechnology. 2016;**34**:78-83. DOI: 10.1038/nbt.3439

[54] Enayati A, Hemingway J. Malaria management: past, present, and

future. Annual Review of Entomology. 2010;**55**:569-591. DOI: 10.1146/annurev-ento-112408-085423

[55] Allan SA. Susceptibility of adult mosquitoes to insecticides in aqueous sucrose baits. Journal of Vector Ecology. 2011;**36**(1):59-67. DOI: 10.1111/j.1948-7134.2011.00141.x

[56] Lea AO. Sugar-baited insecticide residues against mosquitoes. Mosquito News. 1965;**25**:65-66

[57] Schlein Y, Pener H. Bait-fed adult *Culex pipiens* carry the larvicide *Bacillus sphaericus* to the larval habitat. Medical Veterinary Entomology. 1990;**4**:283-288. DOI: 10.1111/j.1365-2915.1990.tb00441.x

[58] Stone CM, Jackson BT, Foster WA. Effects of bed net use, female size, and plant abundance on the first meal choice (blood vs sugar) of the malaria mosquito *Anopheles gambiae*. Malaria Journal. 2012;**11**:3-17. DOI: 10.1186/1475-2875-11-3

[59] Müller G, Schlein Y. Sugar questing mosquitoes in arid areas gather on scarce blossoms that can be used for control. International Journal for Parasitology. 2006;**36**:1077-1080. DOI: 10.1016/j.ijpara.2006.06.008

[60] Beier JC, Muller GC, Gu W, Arheart KL, Schlein Y. Attractive toxic sugar bait (ATSB) methods decimate populations of *Anopheles* malaria vectors in arid environments regardless of the local availability of favoured sugar-source blossoms. Malaria Journal. 2012;**11**:31-37. DOI: 10.1186/1475-2875-11-31

[61] Qualls WA, Xue RD, Revay EE, Allan SA, Muller GC. Implications for operational control of adult mosquito production in cisterns and wells in St. Augustine, FL using attractive sugar baits. Acta Tropica. 2012;**124**:158-161. DOI: 10.1016/j.actatropica.2012.07.004

[62] Müller GC, Junnila A, Qualls WA, Revay EE, Kline DL, Allan SA, et al. Control of *Culex quinquefasciatus* in a storm drain system in Florida using attractive toxic sugar bait. Medical and Veterinary Entomology. 2010a;**24**:346-351. DOI: 10.1111/j.1365-2915.2010.00876.x

[63] Müller GC, Beier JC, Traore SF, Toure MB, Traore MM, Bah S, et al. Successful field trial of attractive toxic sugar bait (ATSB) plant-spraying methods against malaria vectors in the *Anopheles gambiae* complex in Mali. West Africa. Malaria Journal. 2010b;**9**:210-216. DOI: 10.1186/1475-2875-9-210

[64] Hossain TT, Fulcher A, Davidson C, Beier JC, Xue RD. Evaluation of boric acid sprayed on plants against salt marsh mosquitoes, *Aedes taeniorhynchus* (Diptera: Culicidae). Florida Entomologist. 2014;**97**:1865-1868. DOI: 10.1653/024.097.0469

[65] Revay EE, Müller GC, Qualls WA, Kline DL, Naranjo DP, Arheat KL, et al. Control of *Aedes albopictus* with attractive toxic sugar baits (ATSB) and potential impact on non-target organisms in St. Augustine, Florida. Parasitology Research. 2014;**113**:73-79. DOI: 10.1007/s00436-013-3628-4

[66] Tenywal FC, Kambagha A, Saddler A, Maia MF. The development of an ivermectin-based attractive toxic sugar bait (ATSB) to target *Anopheles arabiensis*. Malaria Journal. 2017;**16**:338-347. DOI: 10.1186/s12936-017-1994-6

[67] Xue RD, Ali A, Kline DL, Barnard DR. Application of boric acid baits to plant foliage for adult mosquito control. Journal of the American Mosquito Control Association. 2006;**22**:497-500. DOI: 10.2987/8756-971X(2006)22[497,AOBABT]2.0.CO;2

[68] Gu ZY, He J, Teng XD, Lan CJ, Shen RX, Wang YT, et al. Efficacy of orally toxic sugar baits against contact-insecticide resistant *Culex quinquefasciatus*. Acta Tropica. 2020;**202**:105256. DOI: 10.1016/j.actatropica.2019.105256

[69] Corbel V, Duchon S, Zaim M, Hougard JM. Dinotefuran: a potential neonicotinoid insecticide against resistant mosquitoes. Journal of Medical Entomology. 2004;**41**(4):712-717. DOI: 10.1603/0022-2585-41.4.712

[70] Stewart ZP, Oxborough RM, Tungu PK, Kirby MJ, Rowland MW, Irish SR. Indoor application of attractive toxic sugar bait (ATSB) in combination with mosquito nets for control of pyrethroid-resistant mosquitoes. PLoS One. 2013;**8**:e84168. DOI: 10.1371/journal.pone.0084168

[71] Xue RD, Ali A, Kline DL, Barnard DR. Field evaluation of boric acid- and fipronil-based bait stations against adult mosquitoes. Journal of the American Mosquito Control Association. 2008;**24**:415-418. DOI: 10.2987/5683.1

[72] See AS, Salleh AB, Bakar FA, Yusof NA, Abdulamir AS, Lee YH. Risk and health effect of boric acid. American Journal of Applied Sciences. 2010;**7**:620-627

[73] Fiorenzano JM, Koehler PG, Xue R-D. Attractive toxic sugar bait (ATSB) for control of mosquitoes and its impact on non-target organisms: A review. International Journal of Environmental Research and Public Health. 2017;**14**: 398-410. DOI: 10.3390/ijerph14040398

[74] Keller MD, Leahy DJ, Norton BJ, Johanson R, Mullen ER, Marvit M, et al. Laser induced mortality of *Anopheles stephensi* mosquitoes. Scientific Reports. 2016;**6**:20936. DOI: 10.1038/srep20936

[75] Hori M, Shibuya K, Sato M, Saito Y. Lethal effects of short-wavelength visible light on insects. Scientific Reports. 2014;**4**:07383. DOI: 10.1038/srep07383