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Environmental Manipulation: A Potential Tool for Mosquito Vector Control

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Abstract

Mosquito borne diseases have continued to ravage man and his animals despite efforts to curb its spread. The use of chemicals has been the main thrust for control of all life stages of mosquitoes. Increased resistance to commonly used insecticides has called for renewed effort for vector control. Environmental management for vector control is one of the new strategies developed to tackle the menace of vectors. Manipulation of abiotic factors has widely gained acceptance due to laboratory and semi-field trials and findings. In this chapter, we reviewed literatures on some critical abiotic factors and their effects on bionomics and biological fitness of immature and adult life stages of mosquito species. We also looked at prospects for developing protocols based on these findings.

Keywords: *Aedes*, *Anopheles*, Biological Fitness, *Culex*, Vector Competence

1. Introduction

Mosquitoes are dipterans of the family Culicidae and are important in public health because of the bloodsucking habits of the females and transmission of important human diseases such as yellow fever, malaria, filariasis, and dengue [1]. Mosquitoes have three subfamilies namely, Anophelinae, Culicinae, and Toxorhynchitidae. Among these, only Anophelinae and Culicinae contain medically important Genera (*Aedes*, *Anopheles*, and *Culex*) that are efficient in disease transmission [2]. The discovery of the role played by mosquitoes in disease transmission and the need to develop cost-effective and species-specific control measures, through sound understanding of the biology and ecology of these vectors, have stimulated interest in mosquito research [3, 4].

Mosquitoes have four life stages (egg, larva, pupa, and adult). The egg, larval (comprising of four instars), and pupal stages are all aquatic. Collectively, these stages take about 7 to 14 days to complete development, depending on ambient temperature, as they are cold-blooded. Apart from temperature, other factors also affect the developmental times of mosquitoes. These include photoperiod, density, feed quality and quantity, salinity, hardness, nitrate and sulphate contents, and water pH.

The behaviour of mosquitoes determines their importance/ status as nuisance insects or pathogen vectors, therefore, governs the selection of control methods [5, 6]. Most female mosquitoes depend on blood from animals or humans for

maturation of their eggs [7]. Species that prefer to feed on animals are usually not very effective in transmitting human diseases [8–10], while those that rest indoors are usually the easiest to control [11].

Mosquitoes are the most important insect of public health concern, basically due to their nuisance, ferocious and infective female bites. Diseases spread by female bites, for example, malaria have been responsible for millions of deaths, especially, of pregnant mothers, children below the age of five, and immune-compromised individuals [12, 13]. The brunt of the scourge of mosquito vector-borne diseases (MVDs) is exceptionally high in Tropical and Subtropical climates. This is due in part to clemency of the weather conditions, rapid urbanisation, high anthropogenic activities, proliferation of suitable breeding habitats, among others [14, 15]. In Temperate climes, diseases such as malaria has been eradicated, although, there are risks of reintroduction due to increased human movement and climate change [16]. However, some MVDs, especially, those transmitted by Culicines (e.g., West Nile fever, Dengue, and Chikungunya) are still prevalent and are of significant public health concern in these countries [17]. There is, therefore, need for effective, efficient and eco-friendly vector control tool for mosquito eradication and prevention of disease.

Despite concerted efforts towards mosquito eradication, multi-faceted epidemiological factors have impeded the complete eradication of MVDs, especially in low income countries. These factors include, but are not limited to lack of social and political will from stakeholders, poor budgetary allocations, insufficient manpower, variation in the biology of principal and secondary vectors of the disease. Among these factors, the biology of vector species has received numerous attentions with a lot of scientific publications on the subject matter. In fact, sound knowledge of the biology of mosquito vectors is important for successful implementation of control intervention protocols. This is, exceptionally so, as spatio-temporal variations in biology and genetics of species complex and sibling species [18].

The use of chemical insecticides has been man's foremost weapon against these vectors. However, increased incidence of (cross- and class-) resistance to insecticides by most vector species, with the attendant environmental concerns have necessitated significant reduction in the application or overall ban of some chemical insecticide formulations [19]. There is, therefore, need to develop an alternative robust protocol that would be devoid of the pitfalls of chemical insecticides. Among these alternatives is the integrated vector management (IVM), based on Environmental Management of Vectors (EMVs). The EMVs has proven to be most effective and efficient in this regards [20].

2. Chemical control, the Main thrust of mosquito vector control

Chemical control of mosquito vectors involves the use of chemicals, either synthetic or organic to reduce vector population or contacts with human hosts or their animals. Chemical agents that reduce mosquito vector populations are referred to as chemical insecticides and are usually designed to target various life stages of the mosquitoes. Hence, there are ovicides, larvicides, pupicides, and adulticides, for the control of eggs, larvae, pupae and adult life stages, respectively. Other chemicals produced for control include repellents, oviposition deterrents, among others. Chemical insecticides used in various forms such as aerosols, indoor residual sprays, impregnated household materials, repellents, larvicides among others have contributed, substantially, to the reduction of MVDs in most countries. The introduction and improvement of these chemical agents have mitigated the disease burdens by reducing the vector population.

Despite the initial gains of chemical insecticides in global eradication of vector-borne diseases, cases of increased insecticide resistance have been reported globally. Mosquitoes have developed class- and/or cross-resistance to insecticides, with various mechanisms of resistance (metabolic, physiological, anatomical, or behavioural). Further, environmental studies have shown persistence of some of these chemicals in the environment over decades [21], with cases of destruction and even elimination of non-target and beneficial organisms in the ecosystem. Some degree of mammalian toxicity has also been reported for some of these insecticides. These pitfalls of chemical control methods have necessitated the call for the development of other environmentally safe control protocols which will be efficient and effective in reducing vector population and, hence vectored diseases.

Several alternatives to chemical control methods have been developed against mosquitoes. These include biological, cultural, legal, and genetic control methods. However, the need to integrate these diverse control strategies towards reducing vector population has given rise to Integrated Mosquito Management (IMM).

3. Environmental Management in Integrated Vector Control

A successful larval control protocol requires adequate knowledge of breeding ecology of the vector including, the developmental environmental requirements of the immatures [22–24].

The World Health Organisation (WHO) in 1982, developed the EMVs - a subset of the Concept of Integrated Vector Control - as a roadmap for the control of major vectors and intermediate hosts of diseases. Environmental management activities for vector control involves planning, organisation, carrying out and monitoring activities for the modification and/or manipulation of environmental factors or their interaction with man to prevent or minimise vector propagation and reducing man-vector-pathogen contact [25–27]. Environmental Management of Vector (EVMs) involves three strategies, namely, environmental modification, environmental manipulation, and modification and/or manipulation of human habitation or behaviour to reduce vector-human contact [20].

Environmental Modification involves physical alterations of land, water and vegetation, which are usually permanent or long-lasting, aimed at preventing, removing or reducing the habitats of vectors without causing unduly adverse effects on the quality of the human environment. Activities enlisted under this include drainage, filling, land levelling and transformation and impoundment margins [20]. The second aspect, Environmental Manipulation, consists of any planned recurrent activity aimed at producing temporary conditions unfavourable to the breeding of vectors in their habitats (this is the focus of this chapter). Strategies involved include water salinity changes, stream flushing, water level regulation in reservoirs, dewatering or flooding of swamps or boggy areas, vegetation removal, shading and exposure to sunlight [25].

While, the third aspect, modification of human habitation and/or behaviour, involves strategies that reduce man – vector – pathogen contact. Examples of this approach include siting of human settlements away from vector sources, mosquito proofing of houses, personal protection and hygiene measures against vectors. Others include provision of mechanical barriers and facilities for water supply, wastewater and excreta disposal, laundry, bathing and recreation to prevent or discourage human contact with infested waters, and zoo-prophylaxis, the placement and provision of an alternate blood meal source to divert vectors away from the human blood source [26].

Environmental modification and human habitation and/or behaviour modification have been fully investigated and the outcomes implemented. These results have resulted in major reductions in the epidemiology of the diseases transmitted by some vectors, generally, and mosquitoes in particular. Yet, the diseases vectored by mosquitoes continue to ravage mankind due to either changes in vectors' biology over time, or ineffectiveness of these methods to fit into current trends of Integrated Mosquito Management (IMM) protocols.

Environmental manipulation techniques, on the other hand, provide a sustainable remedy to mosquito vector control, as its ultimate goal is to produce adult mosquitoes which are less fit as vectors by changing the quality of established mosquito breeding habitats. However, environmental manipulation approaches have not been fully exploited, especially, in terms of changing vital developmental components/factors of the vector's environment to reduce biological fitness. Such strategies are promising as they are always targeted at the weakest link (larvae) in development of the vector.

Although these developmental factors act together (antagonistically or synergistically) to affect the growth of mosquitoes in the wild, laboratory studies have shown their individual contribution to vector success. It is hoped that manipulating these developmental components in the wild will produce adult life stages that are less fit as vectors, hence, disrupting the chain of disease transmission [26, 28].

4. Environmental manipulation of mosquito habitats

Integrated Mosquito Management (IMM) protocols based on manipulation of vector's micro-habitat, especially during development, is promising to be an effective strategy in the control of the major disease-causing vectors. The goal of this control approach (Environmental Manipulation) is not to eradicate mosquitoes from the surface of the earth, as it is often advocated, but to identify the environmental factor (s)/variable (s) that contribute (s) to their success, manipulate them to the extent of producing mosquito species which are not fit as vectors of diseases.

Understanding species-specific effects of environmental factor on the bionomics of mosquitoes will be valuable in developing control protocols [20, 26]. One advantage of such protocol is that it will target the weakest link (larvae) during development. Apart from higher vulnerability to toxic materials, larvae are confined within the water body and do not migrate away from toxic environment, unlike adult life stage. More so, application of such protocol would either be species-specific or broad-ranged, depending on the specific developmental requirements of the vectors, and would not require special expertise or training.

5. Abiotic components of mosquito habitats

In mosquito ecology, abiotic components are sometimes referred to as physiochemical factors, and include water conditions such as pH, salinity, hardness, alkalinity, temperature, sulphate, nitrate and phosphate contents, etc. These factors affect mosquito larval bionomics in diverse ways and determine spatio-temporal abundance, distribution and biological fitness of mosquito species. Extensive studies have been carried out either in combination or as a single factor on influence of some of these factors on mosquito biology. With some studies transcending larval bionomics to adult bionomics and filial generations. Mosquitoes have shown limits of tolerance, with some degree of adaptability to these factors.

In nature, physio-chemical factors interact in diverse ways to affect the phenotype and genotype of mosquito species, there is, therefore, need for semi-field and field trials of results from laboratory studies. Further, since there is 'no physiology of mosquito' [29], influence of abiotic factors on specific vector's bionomics is key in understanding their roles in mosquito development and disease transmission.

6. Influence of selected abiotic factors on bionomics of mosquitoes

For the sake of this chapter, a concise and systematic review of the contributions of some abiotic factors to the development of mosquitoes and the possibility of developing novel control intervention will be taken. More elaborate discussions of the subject matter can be found in other publications. Further, the review will be on critical indices of disease transmission in mosquito: duration of development, larval growth rate, immature survivorship, number of adults at emergence, adult longevity and survivorship, wing-based indices, body size, and metabolic reserves.

Duration of development is the time taken to complete pre-imaginal life stages (i.e., from egg to pupae). This is critical to biological fitness as longer developmental times affect resource mobilisation and reduce vector-host contact frequencies [30], among others. Larval growth rate indicates the daily rate of biomass accumulation during the photoperiod (larval stage). It estimates daily weight gain as larvae which is critical to successful adult life traits [31]. Immature survivorship is an index of developmental success of a species, and indicates maternal reproductive success and ensures generation continuity [32].

Number of adults at emergence and sex ratio determines mating frequencies, time before sexual maturity (in male mosquitoes). These are critical for swarming, host-seeking and laying of fertile eggs. Adult longevity and survivorship is an indication of life span of mosquito when fed either energy source alone (sucrose) or in combination with blood meal [32]. These are crucial for extrinsic incubation period within female mosquitoes; disease pathogens complete development in longer-lived adult vector.

Wing-based indices include measurements like wing length, surface area and fluctuating asymmetry. In mosquito physiology, wing length is a proxy for entomological indices such as body size, weight, fecundity [33, 34], longevity [35], host-finding success [36], blood-feeding success [37], survivorship [38] and vectorial capacity; all these influence biological fitness of the vector for disease parasite transmission. Fluctuating asymmetry (FA) is commonly used as a measure of stress during development, and fitness of adult mosquitoes [39, 40].

The body size of adult females influences the number of blood meals acquired and required to complete the first gonotrophic cycle and the number of eggs [41] as smaller females take longer to achieve reproduction and produce fewer off-springs. Metabolic reserves of epidemiological interests are protein, lipid, glucose and glycogen. Most female mosquitoes require blood meals to provision and mature eggs (i.e. fecundity), however, the first ovarian cycle is determined by metabolic reserves, especially that derived from larval nourishment [42]. Autogenous mosquitoes do not require blood meals to lay the first few batches of eggs, unlike anautogenous species, where blood meal in addition to larval-derived nutrient reserves is a prerequisite to laying eggs [43, 44]. Metabolic reserves of newly emerged adults (teneral reserves) affect important female reproductive processes, such as the utilisation of reserves, fecundity, longevity, flight, the formation of new tissues and organs, and blood meal consumption and utilisation [45].

6.1 Water temperature

As cold-blooded organisms, mosquitoes rely on environmental temperature for all metabolic life processes. Literature on influence of temperature on mosquitoes abounds, however, an attempt will be made to summarise these for the sake of this chapter. Temperature zones of the world have been broadly categorised into Tropical/Sub-tropical and Temperate climates. Tropical and sub-tropical climates have relatively high temperatures, while temperate climates have colder to freezing temperatures. The response of mosquitoes from these climates to temperature are different, hence, predictions on development and biology based on prevailing temperatures would be also different [46, 47]. In the tropics and sub-tropics, with all-year-round favourable developmental temperatures, the influence of temperature is extremely strong. Apart from facilitating all year proliferation of mosquitoes, these temperatures also favour development of parasites within the vectors. In temperate climates, however, where extremely cold to freezing temperatures abound, mosquito development is often slow, and at times, halted during adverse weather conditions. These also affect the development of pathogen in the vectors [17].

Information on the influence of temperature on fitness indices at both immature and adult life stages can be employed in developing novel control strategies. Temperature change during development in mosquitoes produce different phenotypes [48–52], endowed with different genotypes. Future genetic studies can be based on these phenotypes.

Mosquitoes are adapted to surviving and reproducing at specific temperature ranges and, thus, have different thermal limits. Temperatures outside these limits lead to disruption of biological processes, or often death. Exposure to high temperatures result in denaturing of proteins, alteration of cell membranes, enzyme structures and properties, pH and ion concentrations, destroying wax complex of the cuticle, leading and desiccation due to evaporation [53].

Genera and species differential responses to lethal temperatures at given time ranges have been reported. Ambient temperature affects mosquito proliferation [54, 55]. Colder temperatures delay embryo eclosion, reduce hatch rate [56], and developmental rate [57]. While higher temperatures elicit faster pupation [58–60], reduced ecdysis [61] and longevity [62].

Olayemi *et al.* [48] reported shorter duration of development in *Cx. quinquefasciatus* mosquito, with increase in temperature: taking as low as 6 days at 34°C. This was, however, accompanied by reduced immature survivorship at temperatures above 30°C for the species. Ukubuiwe *et al.* [49] reported a linear relationship between temperature increase and growth rates and duration of development in *Cx. quinquefasciatus* and a negative relationship between temperature and immature life stages' survivorship. Similar observations have been recorded for *An. gambiae* [57], *Ae. krombeini* [63], and *Cx. tarsalis* [64].

Although high temperatures are associated with faster development, several studies have observed significant reduction in the number of adults at emergence and longevity (with increasing temperature) in mosquitoes such as *Cx. tarsalis* [65], *An. gambiae* [62], *An. sergentii* [66], *Ae. albopictus* [61] and *Cx. quinquefasciatus* [49]. Altering developmental temperature above the upper thermal limit will, therefore, increase immature life stage mortality, reduced adult emergence and human-vector contacts. Temperature change also affect post-emergence longevity in mosquitoes. Adult *Cx. quinquefasciatus* mosquitoes lived the longest at 30°C, whereas, at 34°C, longevity was significantly reduced [49]. High temperatures reduce adult daily survivorship in *Cx. apicinus* and *Cx. hepperi* [67]. In *Cx. quinquefasciatus*, female mosquitoes survived more than the male species at all temperatures investigated [49].

Wing lengths reduce with increase in temperature. This is, however, species-specific. In *Cx. quinquefasciatus*, temperatures above 30°C reduced ptero-fitness [48]. Other researchers have reported similar temperature-dependent variation in adult wing lengths in *An. merus* [68], *An. quadrimaculatus* [50], *Cx. apicinus* [67] and *An. dirus* and *An. sawadwongporni* [51].

Body parts of immature mosquitoes are also affected by water temperature change. Higher water temperatures reduced larval body length, width, and volume and pupal cephalothoracic length in *Cx. pipiens* mosquitoes [40], *An. merus* [68], and *Cx. quinquefasciatus* [52].

There are scanty published data on the influence of temperature on metabolic reserves in mosquitoes. In *Cx. quinquefasciatus*, mosquitoes reared at 34°C had the lowest of all metabolic reserves, while higher reserves were recorded at 30°C [49]. Therefore, for this species, biological fitness of this species is enhanced at 30°C. Therefore, techniques designed to increase developmental temperature above this, will significantly reduce fitness of this vector.

6.2 Water pH

Another important immature breeding factor is water pH. Level of water pH level depends on its carbonic acid equilibrium. Just as for temperature, there are permissible tolerance limits for most aquatic organism, including mosquitoes. Outside these limits, developmental processes and normal physiology are affected [69–71]. Water pH affects availability of essential mineral and food elements for development of mosquitoes, thereby, distribution [72], and survivorship of mosquitoes [73]. Field studies have reported strong positive correlation between pH and the quality of mosquito habitats [72, 74]. Studies have also shown that mosquito larvae adapt to and tolerate fluctuations in ionic levels in these habitats [75–77].

Even though water pH regulates growth in mosquito species, adaptation has been reported in some vector species. For Aedine mosquitoes, species-specific tolerance ranges have been reported [74, 78]. *Culex pipiens* showed limited survivorship at pH 4.4 to 8.5 [79]. At extreme pH values of 4.0 and 10.0, *Cx. quinquefasciatus* had reduced developmental successes and adult biological fitness indices [28]. Its optimum range for development is between pH 5.0 and 8.0. From these studies, it seems that not all habitats in the wild supports development of mosquitoes, however, those that do, might actually reduce biological fitness.

In *Ae. aegypti*, percentage emergence reduced at pH 3.6 and 4.2 [78]. In *Cx. quinquefasciatus*, however, immature survivorship was highest between pH 5.0 and 8.0 and lowest at pH 10.0 [28]. According to the authors, male mosquitoes were most affected by the change in pH levels, and adult survivorship was, exceptionally, high between pH 5.0 to 8.0 and lowest at pH 4.0. Laboratory investigations have revealed larval-age-related increase in reserve accumulation in *Cx. quinquefasciatus* at different water pH level. Rate of mobilisation and accumulation of metabolic reserve components were reduced at extreme water pH conditions and highest at pH 7.0 [28].

6.3 Water hardness

Water hardness levels also play epidemiological roles in regulating the occurrence and distribution of mosquito species. It also determines the quality of mosquito larval habitat [80]. Mostly, the hardness of water is determined by the nature of the topsoil and the presence or absence of divalent cations of calcium (Ca^{2+}), magnesium (Mg^{2+}), ferrous iron (Fe^{2+}) and manganese (Mn^{2+}) ions [81]. Ample evidence has been shown that these ions play protective, metabolic, structural,

and physiologic roles in aquatic organisms [82, 83]. Water hardness levels have been categorised into 'soft', 'slightly hard', 'moderately hard', 'hard' and 'very hard' water with calcium trioxocarbonate (CaCO_3) content, respectively, less than 17.0, 17.0–59.0, 60.0–119.0, 120.0–180.0, and greater than 180 mg/L [84].

Despite the importance of water-hardness-causing ions, mosquitoes perform optimally within set limits [40]. Outside these limits, their occurrence, distribution, physiology, growth and development will be greatly affected. Calcium ions, for example, in excess elicit environmental stress conditions and affect feeding rates of aquatic organisms [85]. Impaired feed intake affects the amount of energy readily available for normal activities of the organisms, and mobilisation from one stage of life to the other [86, 87].

The effects of water hardness on mosquito bionomics have mostly been extrapolated from field data. Field data have suggested that 'moderately' and 'hard' water support mosquito growth [88–93]. Species-specific data on the influence of water hardness is important in elucidating actual contributions to mosquito growth. Hence, Ukubuiwe *et al.* [28, 94] and Aminuwa *et al.* [95] reported the influence of water hardness level on development and morphometric of *Cx. quinquefasciatus*. These authors reported reduced immature developmental successes and adult biological fitness indices of the species at hardness levels ≥ 150 mg/L CaCO_3 (i.e., above 'hard' water). Duration of development of the species was fastest in 'soft' water, but longest in 'very hard' water [28, 95]. Larval growth rates were also highest in 'moderately hard' water but lowest in 'very hard' water [28]. This suggests growth-regulating effect of water hardness on the species, especially when in high quantities.

Further, first instar larvae of *Cx. quinquefasciatus* were most affected by water hardness level change, while immature survivorship of the species was lowest in 'very hard' water. Adult survivorship of *Cx. quinquefasciatus* were highest in 'moderately hard' water CaCO_3 [28]. This study explained the relatively poor productive of habitats with high water 'hardness' content [80] and absence of species in some habitats with 'very hard water' (personal field observations). 'Very hard' water conditions produced very small-sized *Cx. quinquefasciatus* mosquitoes (across all life stages). Wing-based fitness indices for the species were lowest in 'very hard' water [94]). The author concluded that moderately hard water conditions are the best for overall fitness and performance of the species.

Information on the influence of water hardness conditions on metabolic reserves of mosquitoes is also scanty. However, laboratory investigations suggest that as water hardness level increased, mobilisation and utilisation of reserve components increased, resulting in depletion of adult life stage values [28]. These findings have epidemiological implications on population density and degree of human-mosquito contacts for disease pathogens transmission. Therefore, protocols involved in changing hardness levels of mosquito habitats will produce less biologically fit mosquitoes, thereby reducing scourge of the diseases transmitted by these vectors.

6.4 Light duration (photoperiod)

Photoperiod regulates most physiological processes in insects, including growth, diapause and longevity [96–98]. Many insects respond differently to length of day (photoperiod) and depend on it as cue to seasonal development [99–103]. Some insect species develop faster under short day-length, while in others, development is almost halted, and for a few, the insects were indifferent to variation in the day-length [104]. Different mosquito phenotypes are produced on exposure to different photoperiod regimens. Such information could be harnessed for producing small-sized, biologically less fit mosquitoes.

An avalanche of literature exists on the influence of photoperiod on bionomic of mosquitoes. In *Cx. pipiens*, short photoperiodic conditions cause the development of smaller ovarian follicles [105]. These also increase the lifespan in *An. quadrimaculatus* [106], wing length, areas, body weight and greater wing area per unit body weight in *Cx. pipiens pipiens* [107]. In *Toxorhynchites rutilus*, long day-lengths promotes rapid growth and metamorphosis, while short days retards development [108]. In *Wyeomyia smithii* [99], *An. quadrimaculatus* [106, 109], and *An. crucians* [110], short day-lengths has been associated with higher survivorship.

In an extensive study on influence of photoperiod on indices of fitness in *Cx. quinquefasciatus*, Ukubuiwe *et al.* [111] reported shorter durations of development, and higher numbers of adult emergence at short light durations. Exposure of larvae of *Cx. quinquefasciatus* to longer photophase produced phenotypes with shorter wing length and higher fluctuating asymmetry [111]; representing possible developmental stress. Metabolic reserves of the species were also affected by photoperiod conditions; larvae reared at short photoperiods had the highest biomass accumulation. Longer light duration reduced life stages' metabolic reserves and their caloric indices. Larvae of the species reared at longer photo-phase required relatively more metabolic components for pupation and pupal eclosion than those reared in shorter day lengths [112]. Based on the above-mentioned positive influence of short day-lengths on larval and adult fitness indices, it can be concluded that mosquitoes from shorter photophase may prove to be better vectors than those from longer photophase. As these spent the shortest time for development, survived most, were bigger, and accumulated more metabolic reserve than those from longer photoperiodic conditions.

The knowledge and information generated from studies on the effects of photoperiod on vector biology can be incorporated in control strategies that may either retard or slow down the developmental processes or produce less fit adults. Further laboratory studies on vector competence of mosquito species exposed to various photoperiodic regimens are also advocated.

6.5 Larval density/overcrowding

Larval density, described as the number of mosquito per unit, has profound effects on the life cycle of mosquitoes. Most field surveillance of vector species incorporates larval density, often expressed as number of larvae per dip, during larval sampling [113]. Measuring larval density in this regards is generally employed during pre-and post-intervention procedures. The data generated from these exercise tell little or nothing about the contribution of overcrowding to biological fitness of mosquitoes. Through laboratory studies, however, remarkable influence of larval density on various immature and adult life attributes have been elucidated. Such information though laboratory-based, reveals the contribution of larval density and its possible inclusion in developing novel control strategies. Such information will also assist in making informed decisions and the deployment of scarce resources in vector control programs.

High larval density has been associated with various degrees of competitions [114, 115], resulting in phenotypic plasticity in *An. arabiensis* and *An. gambiae* [116] and *Cx. quinquefasciatus* [117]. High larval densities also affect the following indices of biological fitness; immature and adult survivorship, population quality, eclosion rates [118], sex ratio [119], and vector competence [120].

High larval density negatively affects the size and quality of adult *An. gambiae* mosquitoes [121]. According to Ye-Ebiyo *et al.* [122], overcrowded larvae of *An. arabiensis* are often smaller and short-lived as adults. More so, increased larval density has also been linked to sex-specific reactions such as parasite infection [123] and

larval mortality in *An. stephensi* [124] and *Ae. aegypti* [125]. Overcrowding conditions increase larval development times [121], but reduce the size of the mature larva, pupa and resulting adult [126], with its attendant effects on the fecundity of females [127].

In *Cx. quinquefasciatus*, fourth larval instars were most affected by increasing larval density, and resulted in reduced rate of larval growth and immature life survivorship of the species [126]. These authors opined that high larval densities induce stress and reduced feed intake due to competition, with reduction in metabolic reserves. A similar reduction in growth rates have been reported in *Ae. albifasciatus* [128] and *Ae. aegypti* [129].

Although, in nature, gravid mosquitoes tend to avoid ovipositing in habitats that will pose serious developmental tasks on the young larvae as is seen in *An. gambiae* [121]; these laboratory studies explain what might happen when several mosquito species oviposit in habitats, with initial favourable growth factors, which gets exhausted over time.

High larval density significantly affects emergence success, adult survivorship, and longevity in most mosquito vectors: *An. stephensi* [124], *Ae. sierrensis* [130], *Ae. albopictus* [131] and *Ae. aegypti* [132], *Cx. quinquefasciatus* [126, 133], *Cx. pipiens fatigans* [134, 135], *Cx. tarsalis* [136], and *Wyeomyia smithii* [137]. High density also reduce female fecundity in *Ae. aegypti* [125, 138] and *An. gambiae* s.s [131, 139]. Similarly, negative effects of high density have also been reported in *Ae. aegypti*, *Cx. pipiens*, *An. albimanus*, and *An. gambiae* [118], and *Cx. sitiens* [140]. Further, during metamorphosis *Cx. quinquefasciatus* larvae in crowded environments expended more energy for pupation and eclosion. The reason for this is not clear but will lead to depleted energy reserves for adult's life attributes [126].

These observations may imply that higher mosquito larval densities of may not necessarily suggest potential health threat as often reported; as such mosquitoes would have undergone developmental stress, which affects post-immature life traits. Based on the above-mentioned studies, these mosquitoes manifested evidence of developmental stress, such as high fluctuating asymmetry, hence, may be 'bad' fliers, unable to secure mate and forage. More so, these mosquitoes may not live long enough to transmit pathogens, and may not have adequate energetic budgets for intra-vectoral pathogen development as greater energy reserves have been expended for metamorphosis, coupled with low adult survivorship and reduced longevity. Though there are no documented evidence on these submissions, further studies are advocated. However, if the above scenario permits in the wild, it may be nature's way of regulating mosquito population explosion, among others.

7. Prospects

Despite the laboratory evidence from the study of abiotic factors on developmental and adult fitness indices, further studies, either semi-field or field experiments to concretise these observations to enable full integration into control protocol. More so, for effective incorporation of these protocols, the following are gaps of knowledge to be filled.

- **Genetic bases of vector-abiotic factors interaction**

Phenotypic expressions usually have genetic undertones. Genetic studies to decipher the genetic bases of the phenotypes observed in the studies above are highly recommended. The information generated will be useful in genetic manipulations to produce less fit (selective disadvantaged) mosquitoes.

- **Other Abiotic factor**

The influence of other abiotic factors such as sulphate, nitrate, alkalinity, Dissolved oxygen, should also be investigated.

- **Vector competence**

The studies highlighted above did not elucidate the influence of the abiotic factors on the ability of the mosquitoes to develop and transmit disease pathogen. Even though vector competence in mosquitoes has been inferred from the results, further investigated on this is key is understanding the aspect of vectors' physiology.

- **Reproductive performance**

There is also a need to conduct scientific studies on the reproductive performance of females from the regimens of the factors investigated.

- **Generational effects**

Most of the studies reviewed in this chapter ended with the parent stock. No scientific report exists for the influence on the progenies. It would be meaningful to study the effects of the factors on the development and adult fitness indices of subsequent generations. This will provide information on the sustainability of the protocols when developed.

- **Developing Predictive Modelling**

Predictive models will assist in developing protocols to forecast influence of prevailing environmental factors on the biological fitness of mosquitoes, especially in high risks area for maximising control costs.

8. Conclusion

Single vector control approach such as insecticide application has failed to curb the spread of mosquito borne disease and has necessitated development of other techniques such environmental manipulation. Focusing on changing the quality of mosquito breeding habitats to produce less biologically fit adults, in capable of transmitting disease pathogen, environmental manipulation is promising to curb vector population explosion and disease transmission.

9. Recommendation

For effective implementation of environmental manipulation for mosquito vector control, field and semi-field trials of the influence of these critical abiotic factors should be considered. Genetic studies on bases of vector-abiotic factors interactions should be investigated. Other abiotic factors, other than those mentioned in this chapter should be studied. Influence of various abiotic factors on mosquito vector competence and reproductive performance should be explored. The effects of these critical abiotic factors on future generations of parent stocks should also be investigated. Finally, with the information generated, predictive models can be developed.

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Conflict of interests

The authors declare no conflict of interests.

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