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Review Article

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Potential biological control agents for the control of vector mosquitoes: A review

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Abstract

Mosquitoes are a major cause of lethal vector-borne diseases like dengue, malaria, filariasis, chikungunya, and Japanese encephalitis, among other diseases. In a developing country like India, mosquito-borne diseases are significant threats to familiar people as in certain places, there remains low sanitation. Larval and pupal life stages of mosquitoes are mostly confined to tropical and temperate waterbodies and often form a significant proportion of biomass waterbodies. Due to rebound vectorial capacity, resistance to chemical insecticides, and harmful environmental effects, the vector control program has shifted to using biological control agents. These methods are target-specific, eco-friendly, cost-effective, and can be easily deployed. So, the present review is focused on collating and updating the information on the use of aquatic predators, bacterial strains such as *Bacillus* sp. and actinobacterial, algae, and fungi, which are widely used for control of adult mosquitoes in their variety of natural habitats. This review also covers the predation of larvivorous fish and botanical insecticides.

Keywords: aquatic predators; biological control; botanical pesticides; larvivorous fishes; microbial agents; vector mosquitoes

Introduction

Mosquitoes are medically important insects, not only as nuisance biters, but also act as a vector of some harmful pathogens causing dreadful diseases of humans like malaria, dengue, yellow fever, chikungunya, Zika, and Japanese encephalitis among other diseases (Chandra *et al*., 2008a). In 124 tropical and subtropical countries, around 55% of the population is at risk of these diseases (Beatty *et al*., 2007). Malaria is transmitted by ten anopheline species in India of which six are of primary importance. The primary vectors in rural areas are *Anopheles culicifacies* and in urban areas is *Anopheles stephensi*. Malaria affects 36% of the world's population, i.e., 0.241 billion people in 107 countries (World malaria report, 2021). According to WHO (1981), in the South East Asian region, 2.5 million (85.7%) people are at risk of malaria. India alone contributes about 70% of the total cases among the 2.5 million reported cases in South East Asia (Kondrachine, 1992). Approximately 102 million cases of filariasis are primarily transmitted by *Culex quinquefasciatus*. Nearly 1,100 million people are living in areas endemic to Lymphatic filariasis were in most cases either have patent microfilaraeimeia or chronic filarial disease (Michael *et al*., 1996). *Aedes aegypti* is responsible for dengue fever and yellow fever in

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India (WHO, 2017). Dengue infection is endemic in over 100 countries worldwide and each year it causes nearly 100 million cases of dengue fever, 500000 cases of dengue haemorrhagic fever and 24,000 deaths (Gibbons and Vaughn, 2002; Guha-Sapir and Schimmer, 2005). The World Health Organization embrace vector mosquito control as the only measures to prevent or control such diseases. Although interest in biological control of mosquitoes agents was large at the beginning of the 20th century, it is stopped since discovery of the insecticidal properties of the DDT in 1939. But this insecticide has the deleterious effects for health and environment, so alternatives to chemical insecticide become necessary. Currently, the most important measures to control these diseases are mosquito control and personal protection from mosquito bites. Vector control strategies mainly include the use of chemical insecticides, plant-based insecticides, and biological control agents (Poopathi and Tyagi, 2006). In the past several decades, a number of chemical insecticides have been effectively used to control mosquitoes. Constant use of man -made insecticides for mosquito control disrupts natural biological control systems and lead to re-emergence of mosquito populations. It also resulted in the development of resistance in target organisms, harmful effects on non-target organisms and human health problems and subsequently this initiated a search for alternative control measures (Das *et al*., 2007). These problems have prompted researchers to look for alternative vector control agents with high efficacy and low or no adverse effects on environment and human health. The development of new strategies includes natural insecticides which is an important tool to counter the evolution of resistance among the target organisms without affecting the non-target organisms (Cetin and Yanikoglu, 2006). Besides the natural insecticides, biocontrol agents are also given importance in order to combat the population of mosquito as these are target specific, nontoxic to environment, find easy application in the field, cost effective, lack infectivity and pathogenicity in mammals including man and has little and no evidence of resistance in target mosquito species. The use of biological control agents such as predatory fish, bacteria, algae, fungus and aquatic insects had shown promising results to control mosquito populations (Murugesan *et al*., 2009). The present review, work, is the assemblage of a wide range of biological control agents along with their updated information. The objective of the present review is to compile the all-biological control agents which have been reported so far for the control of vector mosquitoes.

Aquatic insects and copepods

Mosquito's life cycle includes stages: egg, larva, pupa, and adult. The first three stages are aquatic, i.e., confined to water bodies provided a high chance for predation to aquatic insects and thus helped in the mosquito control program. Aquatic insects mainly belong to orders such as Coleoptera, Diptera, Hemiptera, and Odonata and are keen to prey upon mosquito larvae. Many of these predators may be shows polyphagous habits, which means they are feeding on a broad range of prey species (generalist predator); some are oligophagous, having a restricted range of prey; or monophagous, having a minimal range of prey; these are also known as specialist predators. Generally, mosquito larvae feeders belong to the polyphagous type (Collins and Washino, 1985). These predators also predate the prey in various ways depending on their mouthparts. Some predators of order Odonata have chewing mouthparts, so they eat their prey. However, predators like beetle larvae and Hemiptera, having a sucking mouth part, suck the prey's body fluid (hemolymph). So, in general, mosquito larvae and pupae are predated by almost all aquatic insect belongs to aquatic Coleoptera (especially Dytiscidae), Hemiptera (especially notonectids), and Odonata, have been observed to consume mosquito larvae as a part of their natural food habits (Peckarsky, 1980). The backswimmer, *Notonecta undulata* (Hemiptera, Notonectidae), has been shown to prey on the second instar of mosquito larvae (Ellis & Borden, 1970). Besides the wide range of aquatic predators from the Phylum Arthropoda (mainly belonging to orders such as Coleoptera, Diptera, Hemiptera, and Odonata), cyclopoid copepods are a diverse group of small crustaceans and have often been used as effective biological control agents against different species of mosquitoes, such as *Anopheles* (Roa *et al*., 2002), *Aedes* (Riviere and Thirel, 1981) and *Culex* (Marten *et al*., 1984). Being microcrustaceans cyclopoid copepods (cyclopoids: a subclass of copepods) are not harmful to human health (WHO, 2009) and have been used to control mosquito larvae of public health importance in artificial containers and under laboratory/field laboratory conditions in some countries like Australia, Thailand, Vietnam, Sri Lanka and to some extent in the Americas (Marten and Reid, 2007a, 2007b; Vu *et al*., 2005). However, predation might occur at any life stage; most research focused on mosquito larval and pupal stages as they are easy to locate. In a single habitat, all three stages are confined. So, field experiments with aquatic insects become easy to carry out. Predating immature stages of mosquitoes seems to be a significant component of mosquito mortality. The major aquatic predator and their prey mosquito species are listed in Tables 1 and 2.

Table 1. List of aquatic predaceous insects and their prey

Name of predator	Order: family of predator	Mosquito prey (larval stage)	References
Acilius sulcatus	Coleoptera: Dytiscidae	*Cx. quinquefasciatus*	Chandra *et al*., 2008b
Agabus erichsoni	Coleoptera: Dytiscidae	*Ae. communis*	Nilsson and Soderstrom, 1988
Colymbetes paykulli	Coleoptera: Dytiscidae	*Culex* sp.	Lundkvist *et al*., 2003
Dytiscus marginicolis	Coleoptera: Dytiscidae	*Culiseta incidens*	Lee, 1967
Lestes congener	Odonata: Lestidae	*Culiseta incidens*	Lee, 1967
Lacconectus punctipennis	Coleoptera: Dytiscidae	*Ae. albopictus*	Sulaiman and Jeffery, 1986
Rhantus sikkimensis	Coleoptera: Dytiscidae	*Cx. quinquefasciatus*	Aditya *et al*., 2006
Toxorhynchites splendens	Diptera: Culicidae	*Cx. quinquefasciatus*	Aditya *et al*., 2006
Aeshna flavifrons	Odonata: Aeshnidae	*Cx. quinquefasciatus*	Mandal *et al*., 2008
Coenagrion kashmirum	Odonata: Coenagrionidae	*Cx. quinquefasciatus*	Mandal *et al*., 2008
Ischnura forcipata	Odonata: Coenagrionidae	*Cx. quinquefasciatus*	Mandal *et al*., 2008
Rhinocypha ignipennis	Odonata: Chlorocyphidae	*Cx. quinquefasciatus*	Mandal *et al*., 2008
Sympetrum durum	Odonata: Libellulidae	*Cx. quinquefasciatus*	Mandal *et al*., 2008
Brachytron pratense	Odonata: Aeshnidae	*An. subpictus*	Chatterjee *et al*., 2007
Crocothemis servilia	Odonata: Libellulidae	*Ae. aegypti*	Sebastian *et al*., 1990
Enallagma civile	Odonata: Coenagrionidae	*Cx. tarsalis*	Miura and Takahashi, 1988
Labellula sp.	Odonata: Libellulidae	*Ae. aegypti*	Bay, 1974
Orthemis ferruginea	Odonata: Libellulidae	*Ae. aegypti*	Sebastian *et al*., 1980
Orthemis ferruginea	Odonata: Libellulidae	*An. pharoensis*	Cordoba and Lee, 1995
Tramea torosa	Odonata: Libellulidae	*An. pharoensis*	Lee, 1967
Trithemis annulata	Odonata: Libellulidae	*An. gambiae*	EL Rayah, 1975
Abedus indentatus	Hemiptera: Belostomatidae	*Cx. annulirostris*	Washino, 1969
Anisops sp.	Hemiptera: Notonectidae	*Cx. annulirostris*	Shaalan *et al*., 2007
Diplonychus sp.	Hemiptera: Notonectidae	*Cx. annulirostris*	Shaalan *et al*., 2007
Diplonychus indicus	Hemiptera: Belostomatidae	*Ae. aegypti*	Venkatesan and Sivaraman, 1984
Buenoa scimitar	Hemiptera: Notonectidae	*Cx. quinquefasciatus*	Rodríguez-Castro *et al*., 2006
Diplonychus rusticus	Heteroptera: Notonectidae	*Cx. quinquefasciatus*	Saha *et al*., 2007
Diplonychus annulatus	Heteroptera: Notonectidae	*Cx. quinquefasciatus*	Saha *et al*., 2007
Anisops bouvieri	Heteroptera: Notonectidae	*Cx. quinquefasciatus*	Saha *et al*., 2007

Enithares indica	Hemiptera: Notonectidae	Anophiline, Culicine and Aedine	Wattal *et al*., 1996
Notonecta sellata	Hemiptera: Notonectidae	*Cx. pipiens*	Fischer *et al*., 2012
Notonecta hoffmani	Hemiptera: Notonectidae	*Cx. pipiens*	Murdoch *et al*., 1984; Chesson, 1989
Anisops breddini	Hemiptera: Notonectidae	*Ae. aegypti*	Weterings *et al*., 2014
Notonecta undulate	Hemiptera: Notonectidae	*Ae. aegypti*	Quiroz-Martinez and Rodriguez-Castro, 2007
Anopheles barberi	Diptera: Culicidae	*Cx. pipiens*	Petersen *et al*., 1969
Anopheles gambiae	Diptera: Culicidae	*An. gambiae*	Koenraadt and Takken, 2003
Bezzia expolita	Diptera: Ceratopogonidae	*Ae. aegypti*	Hribar and Mullen, 1991
Chaoborus crystallinus	Diptera: Chaoboridae	*Ae. aegypti*	Bay, 1974
Ochthera chalybesceens	Diptera: Ephydridae	*An. gambiae*	Minakawa *et al*., 2007
Toxorhynchites amboinensis	Diptera: Culicidae	*Ae. aegypti*	Digma *et al*., 2019
Toxorhynchites brevipalpis	Diptera: Culicidae	Aedes sp.	Gerberg and Visser, 1978
Toxorhynchites Brevipalpis conradti	Diptera: Culicidae	*Ae. africanus*	Sempala, 1983
Toxorhynchites kaimosi	Diptera: Culicidae	*Ae. africanus*	Sempala, 1983
Toxorhynchites rutilus rutilus	Diptera: Culicidae	*Ae. aegypti*	Padgett and Focks, 1981; Focks *et al*., 1982
Toxorhynchites guadeloupensis	Diptera: Culicidae	*Ae. aegypti*	Honório *et al*., 2007
Anisops sardea	Hemiptera: Notonectidae	*Cx. quinquefasciatus*	Mondal *et al*., 2014
Lacotrephes griseus	Heteroptera: Nepidae	*Cx. quinquefasciatus*	Ghosh and Chandra, 2011
Ranatra elongata	Heteroptera: Nepidae	*Cx. quinquefasciatus*	Saha *et al*., 2020
Ranatra filiformis	Heteroptera: Nepidae	*Cx. quinquefasciatus*	Saha *et al*., 2020
Lacotrephes griseus	Heteroptera: Nepidae	*Cx. quinquefasciatus*	Saha *et al*., 2020

Table 2. List of aquatic predaceous copepods (Subphylum: Crustacea; subclass: Copepoda) and their prey species

Name of predator	Mosquito prey (larval stage)	References
Mesocyclops sp.	*Ae. aegypti*	Vu *et al*., 2012
Mesocyclops sp.	*Ae. aegypti*	Vu *et al*., 2005
Mesocyclops sp.	*Ae. aegypti*	Kay *et al*., 2002
Mesocyclops thermocyclopoides	*Ae. aegpyti*	Soto *et al*., 1999
Mesocyclops darwini	*Ae. aegpyti*	Marten *et al*., 1994a,b
Cyclopoid	*An. aquasalis*	Roa *et al*., 2002
Mesocyclops leuckartipilosa	*Ae. aegypti* *Ae. polynesiensis*	Riviere and Thirel, 1981
Macrocyclops albidus *Mesocyclops longisetus*	*Aedes sp* *Anopheles sp.*	Marten *et al*., 1997
Mesocyclops australiensis	*Aedes sp.*	Brown *et al*., 1991
Mesocyclops leuckuarti	*Aedes*	Marten, 1984

Mesocyclops scarassus *Cyclops varicans* *Cyclops languides*	*Anopheles sp.*	Ranathunge *et al*., 2019
Cyclops varicans *Cyclops languides* *Cyclops vernalis* *Mesocyclops leukart* *Mesocyclops scarassus*	*Ae. aegypti* *Ae. albopictus*	Udayanga *et al*., 2019
Macrocyclops albidus *Mesocyclops leukarti*	*Ae. koreicus*	Baldacchino *et al*., 2017
Cyclopoid sp.	*Aedes sp.*	Russell *et al*., 2021
Cyclopoid sp.	*Aedes japonicus*	Linus *et al*., 2019
Calanoid copepod	*Aedes sp.*	Cuthbert *et al*., 2018

Fungi

The search for effective mosquito pathogens that can be used in mosquito control operations has been going on for several years. Both laboratory and field studies have been carried out on those fungi that have shown mosquito larvicide efficacy. Many species of fungi are currently being considered for use in the microbial control of mosquito larvae. Several fungus species of the genus Coelomomyces, Lagenidium, Metarhizium, Culicinomyces, Entomophthora, etc., have a potential biocidal effect against mosquito larvae (Scholte *et al*., 2004). However, some researchers have reported the mode of action of these fungal species, which depicts that they generally affect the cuticle and abdomen of the mosquito larvae (Butt *et al*., 2013). At first, the fungal species spores' adhesion occurs at the mosquito larvae's cuticle. Then the spore becomes generated, penetrating the cuticle where the growth and development occur in the hemocoel (Brian, 2009). The saprophytic feeding starts, fungal re-emergence, and ultimately the larva dies. They are also the possible routes of invasion by the fungus to cause the mortality of larvae (Seye *et al*., 2009). These are the main sites of infection when treated with fungal formulations (Bukhari *et al*., 2011). The attachment and growth of the fungus into the perispiracular valves of the siphon tube causes the blockage of air intake through respiration, thus leading to the death of the larvae (Butt *et al*., 2013).

In Table 3, there is information about the essential fungi which have been reported so far in the mosquito control program.

Table 3. List of fungal species reported against mosquito larvae

Fungal species	Mosquito host	References
Beauveria bassiana	*Culex sp.* *Aedes sp.* *Anopheles Sp.*	Clark *et al*., 1968
Beauveria tenella	*Aedes aegypti* *Aedes dorsalis*	Pinnock *et al*., 1973
Crypticola clavulifera	*Aedes aegypti*	Frances *et al*., 1989
Coelomomyces indicus	*Anopheles arabiensis* *Anopheles culicifacies* *Anopheles gambiae* *Anopheles indificus*	Service, 1977 Service, 1977 Muspratt, 1963 Whisler *et al*., 1999
Coelomomyces lairdi	*Anopheles punctulatus*	Maffi and Nolan, 1977

C. psorophorae var. psorophorae	*Ochlerotus taeniorhynchus* *Aedes cinereus* *Aedes vexans*	Federici and Roberts, 1975; Popelkova, 1982; Mitchell, 1976; Goettel, 1987a
C. stegomyiae var. stegomyiae	*Aedes aegypti* *Aedes albopictus* *Aedes scutellaris*	Shoulkamy *et al*., 1997; Lucarotti and Shoulkamy, 2000; Laird *et al*., 1992; Ramos *et al*., 1996; Padua *et al*., 1986; Laird, 1967
Coelomomyces punctatus	*Anopheles crucians* *Anopheles quadrimaculatus*	Pillai and Rakai, 1970
Conidiobolus destruens	*Culex pipiens*	Mietkiewski and Van der Geest, 1985
Coelomomyces polynesiensis	*Aedes polynesiensis*	Pillai and Rakai, 1970
Coelomomyces maclaeyae	*Aedes polynesiensis*	Pillai and Rakai, 1970
Coelomomyces numularius	*Anopheles squamosus*	Ribeiro and Da Cunha Ramos, 2000
Coelomomyces pentangulatus	*Culex erraticus*	Ribeiro and Da Cunha Ramos, 2000
Coelomomyces angolensis	*Culex guiarti*	Ribeiro, 1992
Culicinomyces bisporales	*Aedes kochi*	Sigler *et al*., 1987
Culicinomyces spp. (unidentified)	*Anopheles amictushilli* *Culex quinquefasciatus*	Sweeney, 1978a
Culicinomyces clavisporus	*Aedes aegypti* *Aedes rubrithorax* *Aedes atropalpus* *epactius* *Anopheles farauti* *Anopheles stephensi*	Cooper and Sweeney, 1982 Frances, 1986 Couch *et al*., 1974 Sweeney, 1978b Couch *et al*., 1974
Culicinomyces clavisporus	*Culex erraticus* *Culex territans* *Culex quinquefasciatus*	Couch *et al*., 1974
Entomophthora culicis	*An. stephensi* *Culex pipiens* *Culex spp*	Kramer, 1982; Roberts, 1974, Roberts and Strand, 1977
Entomophthora conglomerata	*Culex pipiens*	Roberts, 1974
Entomophthora coronata	*Culex quinquefasciatus*	Lowe *et al*., 1968; Low and Kennel, 1972
Entomophthora musca	*Aedes aegypti*	Steinkraus and Kramer, 1987
Eryinia conica	*Aedes aegypti* *Culex restuans*	Cuebas-Incle, 1992
Fusarium oxysporum	*Aedes detritus* *Culex pipiens*	Husan and Vago, 1972; Breaud *et al*., 1980
Fusarium culmorum	*Culex pipiens*	Badran and Aly, 1995
Fusarium dimerum	*Culex pipiens*	Badran and Aly, 1995
Leptolegnia sp. *(Unidentified)*	*Aedes albopictus* *Anopheles gambiae* *Mansonia titillans* *Mansonia dyari*	Fukuda *et al*., 1997 Nnakumusana, 1986 Lord and Fukuda, 1990 Lord and Fukuda, 1990

Leptolegnia chapmanii	*Aedes aegypti* *Culex quinquefasciatus* *Anopheles albimanus* *Anopheles quadrimaculatus*	McInnis and Zattau, 1982; Lord and Fukuda, 1990; McInnis and Zattau, 1982 McInnis and Zattau, 1982
Leptolegnia caudata	*Anopheles culicifacies*	Bisht *et al*., 1996
Lagenidium giganteum	*Aedes aegypti* *Anopheles freeborni* *Culex pipiens*	Rueda *et al*., 1990; Golkar *et al*., 1993 Kerwin *et al*., 1994 Golkar *et al*., 1993; Kerwin *et al*., 1994
Metarhizium anisopliae	*Aedes aegypti* *Aedes albopictus* *Culex quinquefasciatus* *Culex pipiens* *Anopheles stephensi*	Ramoska *et al*., 1981; Daoust *et al*., 1982 Ravallec *et al*., 1989 Ramoska *et al*., 1981; Lacey *et al*., 1988 Daoust and Roberts, 1982
Pythium carolinianum	*Aedes albopictus* *Culex quinquefasciatus*	Su *et al*., 2001
Pythium sierrensis	*Anopheles freeborni* *Culex tarsalis* *Ochlerotus triseriatus* *Uranotaenia anhydor*	Clark *et al*., 1966
Pythium sp.	*Culex tigripes* *Culex quinquefasciatus*	Nnakumusana, 1985
Paecilomyces lilacinus	*Aedes aegypti*	Agarwalda *et al*., 1999
Pythium sp.	*Culex tigripes* *Culex quinquefasciatus*	Nnakumusana, 1985
Smittium morbosum	*Anopheles hilli* *Aedes albifasciatus*	Sweeney, 1981d Garcia et al., 1994
Tolypocladium cylinddrosporum	*Aedes aegypti* *Aedes vexans* *Culiseta inornata* *Culex tarsalis* *Ochlerotus triseriatus*	Goettel, 1988 Goettel, 1987b Goettel 1987b Soares, 1982 Nadeau and Biosvert, 1994
Trichophyton ajelloi	*Anopheles stephensi* *Culex quinquefasciatus*	Mohanty and Prakash, 2000
Verticillium Lecanii	*Ochlerotus triseritus*	Ballard and Knapp, 1984
Zoophthora radicans	*Aedes aegypti*	Dumas and Papierok, 1989

Algae

Mosquito larvae in their aquatic environment feed on microorganisms, small aquatic animals such as rotifers, and other small particulate matter. However, some mosquito larvae also partially or substantially depend on algal mass as a part of their diet (Merritt *et al*., 1992a). Mosquito larvae filter water and algae from the column, and the study suggested that in the gut, after the feeding, algae are generally presented in proportion to their abundance along with the microflora and microfauna (Ranasinghe and Amarasinghe, 2020). Coggeshall (1926) experimented with a pond with high algae production where *Anopheles* sp. is the foremost breeder and found an abundance of algae in their gut and a high population of *Anopheles* sp. in the pond.

Though an abundance of algae in mosquito breeding sites favours their development, some of the algal sp. might be responsible for larval mortality. Purdy (1924) revealed that some algal species could kill mosquito larvae. He found that in the California rice field, there was a dense layer of filamentous algae (blue-green algae) *Tolypothrix* sp., the larvae of *Culex* sp. and *Anopheles* sp. were absent. However, larvae of these mosquito species are found in the nearby pond where these blue-green algae were absent.

The blue-green algae of order Chlorococcales are ill-digested by mosquito larvae. Some of the algae of this order is entirely indigestible (Marten, 2007). Some toxins (such as photometabolite toxic produced by blue-green algae *Anabaena* sp.; microcystins toxic produced by *Oscillatoria agardhii* and *Anabaena circinalis*) released by these algae might be responsible for larval mortality, the same toxin that causes algal bloom in the pond that kills fish and cattle (Ingram and Prescott, 1954). So, algae are not enough, but their toxins might be a point of interest in developing insecticides to control the mosquito population. In Table 4, there is a list of algae that showed the mosquito larvicide activity.

Table 4. List of algal species reported as mosquito larvicide

Algal species	Mosquito species	References
Anabaena unispora	*Aedes aegypti*	Griffin, 1956
Anabaena circinalis	*Aedes aegypti*	Griffin, 1956
Aulosira implexa	*Culex tarsalis*	Gerhardt, 1953
Chlorella ellipsoidea	*Culex quinquefasciatus,*	Dhillon and Mulla, 1981
Rhizoclonium hieriglyphicum	*Aedes aegypti, Culex quinquefasciatus,*	Dhillon *et al*., 1982
Kirchneriella irregularis	*Aedes albopictus*	Marten,1984
Kirchneriella irregularis	*Cx. quinquefasciatus*	Marten, 1986a
Chlorella protothecoides	*Ae. albopictus*	Marten, 1986b
Ulva lactuca, *Caulerpa racemosa*, *Sargassum microystum,* *Caulerpa scalpelliformis,* *Gracilaria corticata,* *Turbinaria decurrens,* *Turbinaria conoides* and *Caulerpa toxifolia*	4th instar larvae of *Aedes aegypti,* *Culex quinquefasciatus,* *Anopheles stephensi*	Syed Ali *et al*., 2013
Westiellopsis sp.	*Aedes aegypti,* *Culex quinquefasciatus,* *Anopheles stephensi and Culex tritaenorhynchus*	Rao *et al*., 1999
Cyanobacteria (blue-green algae)	*Culex* Sp.	Marten, 2007
Selenastrum capricornatum	3rd instar *Cx. quinquefasciatus* larvae	Duguma *et al*., 2017
Ulva lactuca (Chlorophyta), *Padina gymnospora,* *Sargassum vulgare* (Phaeophyta), *Hypnea musciformis,* and *Digenea simplex* (Rhodophyta)	*Aedes aegypti*	Guedes *et al*., 2014
Lobophora variegate, *Spatoglossum asperum, Stoechospermum marginatum, Sargassum wightii,*	*Cx. quinquefasciatus* *Ae. aegypti*	Manilal *et al*., 2011

Acrosiphonia orientalis, Centroceras clavulatum, Padina tetrastromatica		

Larvivorous fish

Now a day, in developed and developing countries, particularly in urban and peri urban areas, malaria control programs alternatively focus on biological control, which includes a wide range of organisms that helps to control mosquito populations naturally through predation, parasitism, and competition. Among them, the use of larvivorous fish was also found to be most effective in the mosquito control program. Biological control is the process of the introduction or manipulation of organisms to suppress vector populations. Since early 1900, all over the world, larvivorous fish have been used extensively as biological mosquito control agents (Chandra *et al*., 2008a).

Larvivorous fish means that they feed voraciously on immature stages of mosquitoes. Some features are required to meet the criteria of larvivorous fishes, such as must be small, hardy, and capable of getting about quickly in shallow waters amid thick weeds where mosquitoes find suitable breeding grounds. They must have the capacity to live in drinking water tanks and pools, move in deep and shallow waters, and withstand drought (Fletcher *et al*., 1992). They must have the capability to survive through rough handling and transportation for long distances. The fish species must be productive breeders with a short life span that can breed in confined water. Another important criterion is that it must be carnivorous and very keen to consume mosquito larvae even in the presence of other food materials, bringing out the outstanding result in regulating the mosquito population. The appearance of larvivorous fish is also a point of selection; it should not be brightly coloured. The fish should not have a nutrition value, so it will not be attractive to fish-eating people (Haq and Srivastava, 2013). Hence, the larvivorous fish should meet the maximum criteria stated above to bring out mosquito control effectively. Tables 5 and 6 represent the list of indigenous and exotic fish as biocontrol agents.

Table 5. Potential indigenous larvivorous fishes as biocontrol agent

Larvivorous fishes	Mosquito species	Reference
Aphanius dispar.	*Culex quinquefasciatus. Anopheles arabiensis. Anopheles gambiae.*	Fletcher 1992; Haq and Srivastava, 2013; Howard *et al*., 2007; Imbahale *et al*., 2011; Ataur-Rahim, 1981
Aplocheilus blockii.	*Anopheles stephensi. Aedes albopictus.*	Menon and Rajagopalan, 1978; Kumar *et al*., 1998
Aplocheilus lineatus.	*Aedes aegypti.*	MESV, 1988
Aplocheilus panchax.	*An. culicifacies. An. sundaicus. Cx. quinquefasciatus. Cx. vishnui.*	MESV, 1988
Colisa fasciatus.	*Mansonioides indiana* Edward, 1930. *Anopheles annularis* Van der Wulp,1884.	MESV, 1988 Sharma and Ghosh, 1989
Colisa lalia.	*An. annularis.*	MESV, 1988
Colisa sota.	*An. annularis.*	MESV, 1988
Chanda nama.	*An. culicifacies. An. balabocensis balabocensis. An. varuna.*	MESV, 1988
Oryzias melastigma.	*Cx. vishnui.*	Sharma and Ghosh, 1989

	Anopheles sp. *Culex sp.*	
Macropodus cupanus.	*Cx. fatigans.*	Mathavan, 1980
Tilapia mossambicus and *Aplocheilus latipes*	*An. sinensis*	Kim *et al*., 2002; Yu and Lee,1989
Oreochromis niloticus	*Cx. quinquefasciatus.*	Ghosh and Chandra, 2017

Table 6. Potential exotic larvivorous fishes as biocontrol agent

Larvivorous fish	Mosquito species	Reference
Carassius auratus	*An. subpictus.* *Cx. quinquefasciatus.* *Ar. subalbatus.*	Chatterjee *et al*., 1997
Gambusia affinis	*An. subpictus.* *Cx. quinquefasciatus.* *An. subalbatus.* *Ae. aegypti.* *An. stephensi.* *An. gambiae.*	Chatterjee and Chandra, 1997 RTDC, 2008 Zvantsov, 2008 Mahmoud, 1985 Imbahale *et al*., 2011
Poecilia reticulata (Guppy)	*An. subpictus.* *An. gambiae.* *An. subpictus.* *An. funestus*	Sitaraman *et al*., 1976; Menon and Rajagopalan, 1978; Sabatinelli *et al*., 1991 Howard *et al*., 2007; Kusumawathie *et al*., 2008 a, b
Xenentodon cancila	*An. subpictus.* *Cx. quinquefasciatus.* *Ar. subalbatus.*	Chatterjee and Chandra, 1996
Oreochromis mossambica (Tilapia)	*Cx. quinquefasciatus.* *An. culicifacies.*	Sharma and Ghosh, 1989
Oreochromis niloticus	*An. gambiae* *An. funestus*	Howard *et al*., 2007; Ghosh *et al*., 2006; Ghosh and Chandra, 2017; Ambrose *et al*., 1993; Kim *et al*., 1994
Nothobranchius guentheri	*Anopheles sp.*	Vanderplank, 1941
Hyphessobrycon rosaceus	*Cx. vishnui*	Barik *et al*., 2018
Puntius tetrazona	*Cx. vishnui*	Barik *et al*., 2018

Bacteria

In biological control, microbial biopesticides also play a significant role in controlling the vector mosquito population. Many researchers have reported some bacterial species that are useful to implement in mosquito control programs. *Bacillus thuringiensis*, *and Bacillus sphericus* can be noble alternatives for synthetic pesticides. For the last two decades, their effectiveness has been reported against *Anopheles*, *Culex*, and *Aedes*. However, *Bacillus sphericus* was reported to be very effective against *Culex* sp. Bacterial strain is more advantageous than synthetic insecticides as they have long-lasting efficacy without affecting non-target organisms and are cost-effective and safest for the ecosystem. It neither eliminates the pathogen nor the disease but brings them into natural balance (Raymond *et al*., 2010). Bacterial strains are isolated from any insect's gut in the biopesticide industry. The soil can be a promising biopesticide agent as it shows long-lasting activity in a polluted environment (Lennox *et al*., 2016). Many authors report the mode of action of these bacterial strains.

The mosquito larvae take up the crystal toxin secreted by the bacterial strain. It solubilizes in the midgut, causes activation of the protoxin by protease into an active toxin, and this toxin binds to specific receptors in the midgut brush border membrane (Bravo *et al*., 2007; Silva-Filha *et al*., 2021). Then probably, toxins' internalization occurs, and cell lysis occurs (Poopathi and Tyagi, 2004). However, bacterial pesticides mentioned above, such as *Bacillus thuringiensis* serotype *israelensis* (*Bti*) and *B. sphaericus*, are highly efficacious against mosquito larvae and have been used since many decades. Another promising bacterial origin, vector mosquito larvicide spinosad, has gained importance in the last decade and is being used in several countries. Spinosad is an insecticide product derived via fermentation from a naturally occurring soil actinomycete, *Saccharopolyspora spinosa* Mertz and Yao. Spinosad contains two insecticidal factors, A and D, in an 85:15% ratio within the final product. Spinosad is found to be highly active by both contact and ingestion of numerous pests in the orders Lepidoptera, Diptera, Thysanoptera, Coleoptera, Orthoptera, Hymenoptera, and others (Hertlein *et al*., 2010). Table 7 shows the list of bacterial strains reported as a mosquito larvicide.

Table 7. List of Bacterial strain reported as a mosquito larvicide

Sl no.	Bacterial strain	Effective against mosquito species	Effect on pupa/ larvae	Reference
1	*Bacillus thuringiensis*	*Anopheles sp.*	Larvae	Balakrishnan *et al*., 2015 Rajendran *et al*., 2018
2	*Bacillus sphericus*	*Culex and Anopheles*	Larvae	Park *et al*., 2010 Balakrishnan *et al*., 2015
3	*Bacillus alvei*	*Culex fatigans, Anopheles stephensi, Aedes aegypti.*	Larvae	Balakrishnan *et al*., 2015
4	*Bacillus brevis*	*Culex fatigans, Anopheles stephensi, Aedes aegypti.*	Larvae	Khyami-Horani *et al*., 1999
5	*Bacillus circulans*	*Cx. quinquefasciatus and Anopheles gambiae and Aedes aegypti.*	Larvae	Darriet and Hougard, 2002
6	*Brevibacillus laterosporus*	*Cx. quinquefasciatus, Aedes aegypti.*	Larvae	de Oliveira *et al*., 2004
7	*Bacillus subtilis*	*Cx. quinquefasciatus.*	Larvae	Balakrishnan *et al*., 2015 Das and Mukherjee, 2006
8	*Clostridium bifermentans*	*Anopheles maculates*	Larvae	de Barjac *et al*., 1990
9	*Pseudomonas fluorescens*	*Anopheles stephensi, Cx. quinquefasciatus, Ae. aegypti.*	Toxic to Larvae and pupa	Jenkins, 1964
10	*Streptococcus species*	*Anopheles sp. and Culex sp.*	Larvae (L3, L4 stage)	Kramer, 1964
11	*Escherichia coli*	*Culex mosquito*	Larvae (early inster)	Jenkins, 1964
12	*Bacillus cereus*	*Anopheles sp. and Culex sp.*	Larvae	Balakrishnan *et al*., 2015
13	*Bacillus amyloliquefacien*	*Anopheles sp*	Larvae and pupae	Geetha *et al*., 2014
14	*Aneurinibacillus aneurinilyticus*	*Anopheles subpictus, Cx. quinquefasciatus, Aedes aegypti.*	Larva	Das *et al*., 2016

15	*Bacillus sphaericus*	*Anopheles subpictus, Cx. quinquefasciatus, Armigeres subalbatus*	larva	Das *et al*., 2017
16	*Saccharopolyspora spinosa*	*Aedes aegypti An. albimanus An. pseudopunctipennis*	larva	Bond *et al*., 2004
		Aedes aegypti	larva	Perez *et al*., 2007
		Aedes aegypti	larva	Antonio *et al*., 2009
		Aedes aegypti An. stephensi Cx. pipiens	larva	Romi *et al*., 2006
		Aedes aegypti	larva	Darriet and Cerbel, 2006
		Aedes aegypti An. gambiae Cx. quinquefasciatus	larva	Darriet *et al*., 2005
		Aedes aegypti	larva	Ayesha *et al*., 2006
		Ae. albopictus	larva	Liu *et al*., 2004 a
		Cx. quinquefasciatus	larva	Liu *et al*., 2004b
		An. sinensis	larva	Shin *et al*., 2003
		Cx. pipiens	larva	Cetin *et al*., 2005
		Cx. Pipiens	larva	Bahgat *et al*., 2007
		Cx. quinquefasciatus Ae. aegpti	larva	Jiang and Mulla, 2009
		Cx. quinquefasciatus	larva	Sadanandane *et al*., 2009
		Cx. quinquefasciatus	larva	Sadanandane *et al*., 2018

Mosquito control by plant products

Insecticides of botanical origin can play an essential role in the interruption of the transmission of mosquito-borne diseases. These insecticides act as a larvicide, pupicide, repellent, oviposition deterrent, or fumigants to control the mosquito population. So, insecticides of plant origin are mainly secondary metabolites such as alkaloids, steroids, terpenoids, tannins, and flavonoids deposited in the plant for their defence purposes. Earlier Shaalan *et al.* (2005) reported that secondary metabolites from different plant species have insecticidal properties. These secondary metabolites are extracted from the plant that is either built in the body of the herb or various parts of larger plants like fruits, leaves, stems, barks, roots, etc. So, variation in insecticidal properties of these phytochemicals depends on the plant species and the geographical distribution of the plant (Chowdhury *et al*., 2008a). Besides that, extraction methodology and the polarity of the solvent used for the extraction process are also supportive forces to define the insecticidal properties of phytochemicals (Chowdhury *et al*., 2008b). After the solvent extraction, phytochemicals containing the active principle for their mosquitocidal activity are concentrated and ready for application in the mosquito control program. Here an attempt is made to give an account of the plants that has been reported so far as an insecticidal agent against various life forms of mosquito species (Table 8).

Table 8. List of plants and plant parts reported so far as mosquitocidal agent

Plant species	Family	Plant parts used	Target mosquito species	References
Artemisia annua	Asteraceae	Leaf	*Anopheles stephensi*	Sharma *et al*., 2006
Acacia nilotica	Fabaceae	Leaf	*Anopheles stephensi*	Saktivadivel and Daniel, 2008
Argemone mexicana	Papaveraceae	Leaf, Seed	*Culex quinquefasciatus*	Karmegan *et al*., 1997
Jatropha curcas	Euphorbiaceae	Leaf	*Culex quinquefasciatus*	Rahuman *et al*., 2007
Carica papaya	Caricaceae	Seed	*Culex quinquefasciatus*	Rawani *et al*., 2009
Murraya paniculata	Rutaceae	Leaf	*Culex quinquefasciatus*	Rawani *et al*., 2009
Aloe barbadensi	Liliaceae	Leaf	*Anopheles stephensi*	Maurya *et al*., 2007
Solanum xanthocarpum	Solanaceae	Root	*Culex pipiens pollens*	Mohan *et al*., 2006
Cleistanthus collinus	Euphorbiaceae	Leaf	*Culex quinquefasciatus*	Rawani *et al*., 2009
Eucalyptus globulus	Myrtaceae	Seed, Leaf	*Culex pipiens*	Sheeren *et al*., 2006
Thymus capitatus	Lamiaceae	Leaf	*Culex pipiens*	Mansour *et al*., 2000
Citrus aurantium	Rutaceae	Fruit peel	*Culex quinqefasciatus*	Kassir *et al*., 1989
Myrtus communis	Myrtaceae	Flower and leaf	*Culex pipiens molestus*	Traboulsi *et al*., 2002
Alternanthera sessilis	Amaranthaceae	Leaf	*Cx. quinquefasciatus*	Rawani *et al*., 2014
Ruellia tuberosa	Acanthaceae	Leaf	*Cx. quinquefasciatus*	Rawani *et al*., 2014
Trema orientalis	Cannabaceae	Leaf	*Cx. quinquefasciatus*	Rawani *et al*., 2014
Gardenia carinata	Rubiaceae	Leaf	*Cx. quinquefasciatus*	Rawani *et al*., 2014
Piper nigram	Piperaceae	Seed	*Culex pipiens*	Shaalan *et al*., 2005
Euphorbia hirta	Euphorbiaceae	Stem bark	*Culex quinquefasciatus*	Rahuman *et al*., 2007
Polianthes tuberosa	Agavaceae	Bud	*Cx. quinquefasciatus An. stephensi*	Rawani *et al*., 2012
Ocimum basilicum	Lamiaceae	Leaf	*Anopheles stephesnsi, Culex quinquefasciatus*	Maurya *et al*., 2009
Momordica charantia	Cucurbitaceae	Fruit	*Anopheles stephensi*	Singh *et al*., 2006
Kaempferia galanga	Zingiberaceae	Rhizome	*Culex quinquefasciatus*	Choochote *et al*., 1999
Khaya senegalensis	Meliaceae	Leaf	*Culex annulirostris*	Shaalan *et al*., 2005

Acacia auriculiformis	Fabaceae	Fruit	*Culex vishnui*	Barik *et al*., 2018
Curcuma aromatica	Zingiberaceae	Rhizome	*Aedes aegypti*	Choochate *et al*., 2005
Cybistax antisyphilitica	Bignoniaceae	Stem Wood	*Aedes aegypti*	Rodrigues *et al*., 2005
Eucalyptus citriodora	Myrtaceae	Leaf	*Anopheles stephensi, Culex quinquefasciatus, Aedes aegypti*	Singh *et al*., 2007
Solanum nigram	Solanaceae	Dried fruit	*Anopheles culicifacies, Anopheles stephensi*	Raghavendra *et al*., 2009
Tridax procumbens	Compositae	Leaf	*Anopheles subpictus*	Kamaraj *et al*., 2011
Ageratum conyzoides	Asteraceae	Leaf	*Culex quinquefasciatus*	Saxena *et al*., 1992
Cleome icosandra	Capparaceae	Leaf	*Culex quinquefasciatus*	Saxena *et al*., 1992
Ageratina adenophora	Asteraceae	Twigs	*Culex quinquefasciatus, Aedes aegypti*	Raj Mahan and Ramaswammy, 2007
Feonia limonia	Rutaceae	Leaf	*Culex quinquefasciatus, Aedes aegypti, Anopheles stephensi*	Rahuman *et al*., 2000
Millingtonia hortensis	Bignoniaceae	Leaf	*Culex quinquefasciatus, Anopheles stephensi, Aedes aegypti*	Kaushik and Saini, 2008
Ocimum sanctum	Labiate	Leaf	*Aedes aegypti, Culex quinquefasciatus*	Anees, 2008
Eucalyptu globulus	Myrtaceae	Seed and leaf	*Culex pipiens*	Sheeren, 2006
Phumbago zeylanica, P. Dawei, P. stenophylla	Plumbaginaceae	Root	*Anopheles gambiae*	Maniafu *et al*., 2009
Euphorbia tirucalli	Euphorbiaceae	Latex and stem bark	*Culex pipiens pallens*	Yadav *et al*., 2002
Nyctanthes arbortristis	Nyctantheceae	Flower	*Culex quinquefasciatus*	Khatune *et al*., 2001
Citrus sinensis	Rutaceae	Fruit peel	*Anopheles subpictus*	Bagavan *et al*., 2009
Aloe ngongensis	Asphodelaceae	Leaf	*Anopheles gambie*	Matasyoh *et al*., 2008
Millettia dura	Leguminosae	Seed	*Aedes aegypti*	Yenesew *et al*., 2003
Cassia obtusifolia	Leguminosae	Seed	*Aedes aegypti, Aedes togoi, Culex pipiens pollens*	Yang *et al*., 2003
Atlantia monophylla	Rutaceae	Leaf	*Anopheles stephensi*	Sivagnaname and Kalyanasundaram, 2004

Dysoxylum malabaricum	Meliaceae	Leaf	*Anopheles stephensi*	Senthil Nathan *et al.*, 2006a
Melia azedarach	Meliaceae	Leaf and seed	*Anopheles stephensi*	Senthil Nathan *et al.*, 2006b
Moringa oleifera	Moringaceae	Bark	*Culex gelidus*	Kamaraj and Rahaman, 2010
Ocimum gratissimum	Lamiaceae	Leaf	*Culec gelidus*	Kamaraj and Rahaman, 2010
Solenostemma argel	Apocynaceae	Aerial part	*Culex pipiens*	Al- Doghaini *et al.*, 2004
Chrysanthemam indicum	Asteraceae	Leaf	*Culex tritaeniorhynchus*	Kamaraj *et al.*, 2010
Mormordica charantia	Cucurbitaceae	Leaf	*Culex quinquefasciatus*	Prabhakar and Jebanesan, 2004
Vitex negundo	Verbenaceae	Leaf	*Culex quinquefasciatus*	Krishnan *et al.*, 2007
Centella asiatica	Umbelliferae	Leaf	*Culex quinquefasciatus*	Rajkumar and Jabanesan, 2005
Pavonia zeylanica	Malvaceae	Leaf	*Culex quinquefasciatus*	Vahitha *et al.*, 2002
Coccinia indica	Cucurbitaceae	Leaf	*Culex quinquefasciatus, Aedes aegypti*	Rahuman *et al.*, 2007
Cassia tora	Caesulpinaceae	Seed	*Aedes aegypti, Culex pipiens pallens*	Jang *et al.*, 2002
Annona squamosa	Annonaceae	Leaf	*Anopheles sp.*	Das *et al.*, 2007
Chamaecyparis obtusa	Cupressaceae	Leaf	*Anopheles stephensi*	Jang *et al.*, 2005
Acalypha alnifolia	Euphorbiaceae	Leaf	*Anopheles stephensi, Aedes aegypti, Culex quinquefasciatus*	Kovendan *et al.*, 2012
Solamum villosum	Solanaceae	Leaf, Berry	*Anopheles subpictus, Aedes aegypti*	Chowdhury *et al.*, 2008a, 2008b, 2009
Cestrum diurmum	Solanaceae	Leaf	*Anopheles stephensi*	Ghosh and Chandra, 2006
Solamum nigrum	Solanaceae	Leaf, berry	*Culex quinquefasciatus*	Rawani *et al.*, 2010, 2013
Cassia obtusifolia	Leguminosae	Leaf	*Anpheles stephensi*	Rajkumar and Jabanesan, 2009
Apium graneolens	Umbelliferae	Seed	*Aedes aegypti*	Choochate *et al.*, 2004
Rhizophora mucronata	Rhizophoraceae	Bark, pith, stem Wood	*Aedes aegypti*	Kabaru and Gichia, 2009
Piper langum	Piperaceae	Fruit exocarp	*Aedes aegypti*	Chaithong *et al.*, 2006

Conclusions

For the vector control Programme, an abundance of strategies has been developed and are being adopted in different parts of the world. In the present review work, emphasis has been given towards the use of biological control agents as the most effective tool for the control of the vector mosquito population. An effort has been given to control the immature stages of mosquitoes by using biological control agents. In mosquito control programmes, larval forms are a point of attraction because there are confined in water bodies and are easy to locate and control. The development of resistance and adverse effect of synthetic insecticides on the environment and other non-target organisms has shifted the research effort toward an alternative way to reduce the mosquito menace. Over the past few years, biological control of mosquitoes has been given more importance to develop safer methods regarding toxicity to man, the environment and other non-target organisms. So biological control of vector mosquitoes includes using aquatic insects, copepods, and larvivorous fish as a predator of mosquito larvae; the use of pathogens like algae, fungi, and bacteria, and insecticides of plant origin. Since a single method of control cannot be enough to bring out the desired results, importance should be given to the multiple vector mosquito control approaches, including insecticides, biocontrol agents, and environmental management.

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The author read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

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Conflict of Interests

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