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The future of mosquito control: The role of spiders as biological control agents: A review

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Abstract
Mosquitoes have tremendous impact on human health as vectors of serious diseases such as malaria. The use of biological control means on mosquitoes has so far shown promising results, although this approach needs more elaborate research. Spiders have a wide insect host range and thus can act as biological control agents of insect pests. The objective of this review was to explore factors, mechanisms and responses of spiders toward mosquitoes so that introduction, augmentation or conservation of spiders in areas where malaria is endemic can be adopted. Reports on mosquito-eating spiders and incidents of spiders acting as biological control agents have been reviewed. A better understanding for the mosquito-predator relationships could lead to satisfactory reduction of mosquito-borne diseases by utilizing them in biological control programs and/or integrated control. Two species of spiders specialised in seeking and destroying mosquitoes, *Evarcha culicivora* spider from East Africa, *Crossopriza lyoni* a common inhabitant of homes in the rural villages of Thailand and *Paracyrba wanlessi* from Malaysia, could contribute to strategies to fight malaria in respective geographical areas.

Keywords: Mosquito, predator, vector, biological control, spider

Introduction
Developing more effective ways to manage mosquitoes using their natural enemies, “biological control” is critical for two reasons. First, mosquitoes continue to be a major health problem in almost all tropical and subtropical countries in this present era of climate change. They are responsible for transmitting pathogens which cause life-threatening diseases such as malaria, yellow fever, dengue fever and filariasis. Recently, new threats of viral diseases such as zika and chikungunya, spread by mosquitoes have also emerged [1]. Secondly, the convenience of insecticides is threatened by the declining availability of products as a result of resistance in pest populations rendering them ineffective as well as increasingly stringent regulatory demands for human and environmental safety. Some chemicals for domestic pest control destroy arthropods such as spiders and ants. With this practice, the mosquitoes lose their natural enemies which would otherwise have kept their populations in check. Therefore, a search for new environmentally friendly control measures was initiated and agents that act directly on mosquitoes’ life cycle, their feeding patterns and the ability of adult forms to spread diseases are needed. This paper reviews researches that have explored possibilities of using mosquito-predator relationships in the control of mosquitos as vectors of disease causing pathogens specifically highlighting the potential use of spiders.

Biological control of Mosquitoes
Biological control refers to the introduction or manipulation of organisms to suppress vector populations [2]. Several biological mosquito control techniques that have been used include the direct introduction of parasites, pathogens and predators to target mosquitoes [3]. Sarwar (2015) [4] provides three key ways of using biological control of mosquitoes in the field, namely, conservation of existing natural enemies, introducing new natural enemies and establishing a permanent enemy population by mass rearing and periodic or seasonal release.
Mosquitoes have a number of natural enemies that collectively influence their populations. All natural predators such as birds, fish, dragonflies, bats, purple martins and others organisms play a part in mosquito control by targeting different life cycle stages, but not to the extent that is viable, especially during times of peak mosquito numbers, for example, after flooding or storms.

Several researchers have explored a number of predators as biological control agents of mosquitoes. These predators may have limited effect on eradicating populations of mosquitoes, but the role of mosquitoes as a prey species is an important consideration for their control. Waage and Greathead (1988) [5] advise that selection of biological control agents should be based on their potential for unintended impacts, self-replicating capacity, climatic compatibility, and their capability to maintain very close interactions with target prey populations.

Among the mosquito biological control agents are the larvivorous, top minnow fish, *Gambusia affinis,* which were extensively introduced into potential mosquito breeding habitats of the world since the early 1900s [1, 2]. The fish, is an opportunistic predator with a highly variable diet that includes algae, zooplankton, aquatic insects, as well as eggs and young ones of other native fish and amphibians [2].

The copepod crustaceans, *Mesocyclops* and *Macrocyclops* species, have been used for the biological control of *Aedes* mosquitoes in French Polynesia [6] and in Queensland, Australia [7]. They mainly feed on the first instar larvae. These findings have led to simple protocols for culturing copepods species being established for maintenance and mass propagation before release [8].

Mermithid nematodes parasitizing mosquitoes have substantial potential for vector control [9, 10]. Mermithid nematodes, such as *Diximermis peterseni* [11], *Romanomermis iyengari* [12], and *Strelkovimermis spiculatus* [13] were evaluated for the development of biological control of mosquitoes. All mermithid nematodes were observed to infect the larval stages of their hosts. However,_there are_some environmental limitations of mermithid nematodes as biological control agents. For example, Petersen (1973) [14] reported that *Romanomermis culicivorax* was infective only in the 20-32ºC range and pH 5.4 to 7.9. Temperature and pH are therefore an important considerations in the use of *Romanomermis culicivorax* as a biological control agent. Brown and Platzer (1978) [15] reported on the inability of *Romanomermis culicivorax* to infect mosquitoes under low oxygen conditions. Petersen and Willis (1970) [16] also reported that mild salinity of 0.04M NaC1 inhibited the infectivity of *Romanomermis culicivorax*. Therefore, it appears that *Romanomermis culicivorax* would not be an effective biocontrol agent in wastewater situations such as in sewage ponds where mosquitoes commonly breed.

Several microorganisms have been reported to show success in controlling mosquitoes, especially at the larval stage. The larvicidal toxins produced by *Bacillus thuringiensis subsp israelensis* (Bti*)* and *Lysinibacillus sphaericus* (Ls) have been used in biological control since their discovery [17]. The obligate intracellular bacterium, *Wolbachia* was also observed to reduce the survival and development of *Aedes. aegypti* larvae, indicating_its potential as dengue biological control agent [18]. The use of fungi as biological control agents for mosquitoes was investigated by Dabro *et al*., (2012) [19] using the entomopathogenic fungus *Beauveria bassiana*. This species was observed to reduce the survival rate, blood-feeding success, and fecundity in *Aedes aegypti*. Another fungal pathogen, *Metarhizium anisopliae*, was found to be pathogenic to a wide range of mosquitoes in the genera of *Aedes* and *Culex* [20]. Huang *et al., (*2017) [17] however, recommend that it is impossible to provide a comprehensive list of microorganisms that can act as biological control agents of mosquitoes and there is need to guard against the off-target effects to other arthropod species in the process of formulating microorganism-based biological control strategies.

Diversity of spiders

Spiders (Order Araneae) are considered the seventh largest arthropod group [21] found in all continents, with fossils dating back to about 380 million years ago and having a current diversity of over 42 751 described species placed in 3 859 genera and 110 families [22]. Spiders stand out because of their ecological importance as the dominant non-vertebrate predators in most terrestrial ecosystems [23].

Spiders can be divided into two groups depending on how they capture their prey. Web-building spiders construct webs in undisturbed habitats to capture their prey. They live in or near their web and wait for the prey to come to them. They rely on sensing vibrations in their web to detect prey.

Hunting spiders do not construct webs to capture their but, instead, they rely on speed and eyesight to chase and capture prey. These hunters may be divided into active hunters search for and chase their prey and passive hunters which lie in wait and seize their prey as it approaches. Table 1 summarises some common spider families found in agroecosystems.

Table 1: Common spider families, genera, and species found in agroecosystems. [Adapted from Maloney *et al*., 2003 [24]]

Family	Common Name	Genus or Species
Web-Weaving Spiders		
Araneidae	Orb-weaving Spiders	*Argiope* spp
Agelenidae	Funnel-Web Spiders	*Agelena labyrinthica* (Clerck)
Tetragnathidae	Long-jawed Spiders	*Tetragnatha laboriosa* Hentz
Theridiidae	Cob-Web Spiders	*Latrodectus mactans*
Hunting Spiders		
Pisauridae		*Pisaurina mira* (Walckenaer)
Clubionidae	Sac spiders	*Cheiracanthium inclusum* (Hentz) *Cheiracanthium mildei* Koch *Clubiona* spp.
Lycosidae	Wolf Spiders	*Rabidosa rabida* (Walckenaer) *Lycosa antelucana* Montgomery *Pardosa pseudoannulata* (Bösenberg et Strand) *Hogna* spp. *Pardosa* spp. Oxyopidae Lynx Spiders *Oxyopes saltic*
Oxyopidae	Lynx Spiders	*Oxyopes salticus* Hentz *Peucetia viridans* (Hentz)
Salticidae	Jumping spiders	*Phiddipus audax* (Hentz) *Pelegrina galathea* (Walckenaer)

Spiders as predators of mosquitoes

Spiders have largely been overlooked as predators of mosquitoes and its larvae in various ecosystems, yet they play an important role as stabilizing agents or regulators of insect populations in agro-forest and other terrestrial ecosystems [25]. Their presence in an ecosystem may well influence the population dynamics of other arthropods present [26]. Ferguson *et al*., (1984) [27] and Whitmore *et al.,* (2002) [28] reported that spiders had also been found to have great potential to serve as biological control agent against crop pests. Several studies have shown that insect populations significantly increase when released from predation by spiders [24]. Hadole and Vankhede, (2012) [2] described the life span of most spiders ranging from 8 to 10 months and their life cycles mostly synchronises with the periods of life cycles of mosquitoes, as both of them prefer humid and warm environments.

A study conducted in Bharatpur, District of Rajasthan, India on spider families that fed on mosquitoes showed the predatory potential of seven spider families on larvae and adults of mosquitoes. The spiders families included Araneidae, Salticidae, Pholcidae, Oxyopidae, Tetragnathidae, Lycosidaeand Pisauridae [25]. (Table 2). It was observed that the families Tetragnathidae, Lycosidae, Pisauridae and Trechaleidae fed on mosquito larvae while species of spiders from Araneidae, Salticidae, Pholcidae and Oxyopidae families predated on flying mosquitoes. Their results also showed the rank wise sequence of the spider families based on the consumption of larvae and adults of mosquitoes, as follows:

On the mosquitoes larvae: Lycocidae > Tetragnathidae > Pisauridae > Salticidae> Araneidae > Oxyopidae > Salticidae.

On the adults mosquitoes: Salticidae > Araneidae > Oxyopidae > Pholcidae >Lycocidae > Pisauridae > Tetragnathidae.

Table 2: List of spider families and species, employed as predators on mosquitoes (Adapted from Lawania *et al*., 2013 [25])

Family	Species	Habitat
Araneidae	(i) *Argiope aemula*	Gardens
	(ii*) Argiope anasuja*	Gardens
Lycosidae	(i) *Lycosa pictula*	Common in grassland, near water bodies
	(ii) *Perdosa biramnica*	Common in grassland, near water bodies
Oxyopidae	(i) *Oxyopes biramanicus*	Grass and low shrubs
	(ii) *Oxyopes sp.*	Grass and low shrubs
Pholcidae	(i) *Artema atlanta*	Human habitation
	(ii) *Pholcus phalangiodes*	Human habitation
Salticidae	(i) *Plexippus paykuli*	Bushes and medium size plants
	(ii) *Phidippus pateli*	Walls of buildings and tree trunks
Tetragnathidae	(i) *Leucauge decorate*	Gardens near water bodies
	(ii) *Leucauge sp.*	Gardens near water bodies
Pisauridae	(i) *Pisaura sp.*	Gardens near water bodies

Nelson *et al.,* (2005) [29], Ximena *et al.* (2005) [30] and Jackson *et al*., (2014) [31], investigated the prey-capture behaviour of *Evarcha culicivora*, an East African mosquito-eating jumping spider, on two mosquito species, *Anopheles gambiae sensu stricto* and *Culex quinquefasciatus*. When tested with live mosquitoes, small juveniles of *E. culicivora* were observed to be more effective at capturing *Anopheles* than *Culex*. Large juveniles of *E. culicivora* were more effective than small juveniles at capturing *Culex*, but large and small juveniles had similar success at capturing *Anopheles*. Moreover, they observed that generally *E. culicivora* chose blood-fed *Anopheles* significantly more often than blood-fed *Culex* and chose sugar-fed *Anopheles* significantly more often than sugar-fed *Culex,* and chose sugar-fed *Anopheles* significantly more often than midges. Jackson and Nelson (2012) [32] discovered that *E. culicivora* preyed on mosquitoes, especially females engorged after a blood meal. Generally, salticids like *E. culicivora* have unique, complex eyes and an ability to see prey in remarkably fine detail [33, 34]. Furthermore, Cross and Jackson (2011) [35], have pointed out that vision is not the only sensory modality that *E. culicivora* uses in identifying its prey but olfaction as well. These spiders use their olfaction to discern if a mosquito has just taken a blood meal based on the tilt of their abdomens, and then they pounce. This behaviour, according to Jackson and Cross (2015) [36], is unique and no other animal targets its prey based on what that prey has eaten (Figure 1(A). Furthermore, by eating blood-filled mosquitoes, these spiders of both sexes seem to acquire a "perfume" that makes them more attractive to potential mates. That means they kill blood-carrying mosquitoes for food as well as for sex.

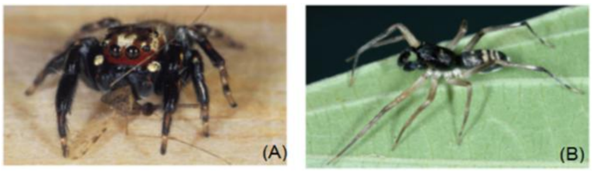

Fig 1(A): Adult male of *Evarcha culicivora* preying on *Anopheles gambiae* (B) Adult male of *Paracyrba wanlessi.* [Source: Jackson and Cross 2015] [36]

Jackson *et al.*, (2014) [31] investigated *Paracyrba wanlessi*, a Southeast Asian jumping spider (Araneae Salticidae) that lives in the hollow internodes of fallen bamboo (Figure 1(B)). Like *E. culicivora*, *P. wanlessi* was observed to have a strong preference for mosquitoes as prey and yet the two spiders have distinctively different preference profiles. Their findings showed that *P. wanlessi* choose mosquitoes significantly more often than a variety of other prey types, regardless of whether the prey were in or away from water, and regardless of whether the mosquitoes were adults or juveniles. *E. culicivora* and *P. wanlessi* also live in rather different habitats. Table 2 gives a summary of the comparison between *E. culicivora* and *P. wanlessi*.

Table 3: Comparison between *Evarcha culicivora* and *Paracyrba wanlessi* (Family Salticidae) [Source: Jackson and Cross 2015] [36]

	E. culicivora	***P. wanlessi***
Locality	Western Kenya	Peninsular Malaysia
Habitat	Walls of buildings	Culms of bamboo
Adult mosquitoes (terrestrial prey) dominant in natural diet	Yes	Yes
Juvenile mosquitoes (aquatic prey) dominant in natural diet	No	Yes
Chooses adult mosquitoes in preference to other terrestrial prey	Yes	Yes
Chooses blood-carrying mosquitoes in preference to non-blood-carrying prey	Yes	No
Chooses adult female mosquitoes in preference to adult male mosquitoes even in absence of blood	Yes	No
Chooses adult anopheline mosquitoes in preference to adult non-anopheline mosquitoes even in absence of blood	Yes	No
Chooses juvenile mosquitoes in preference to other aquatic prey	N/A	Yes
Chooses non-mosquito prey in water in preference to non-mosquito prey away from water	N/A	Yes
Chooses juvenile mosquitoes in water in preference to juvenile mosquitoes away from water	N/A	Yes
Chooses adult mosquitoes away from water in preference to non-mosquito prey in water	N/A	Yes
Chooses adult mosquitoes in water in preference to non-mosquito prey in water	N/A	Yes
Chooses adult mosquitoes in water in preference to adult mosquitoes away from water	N/A	Yes
A versatile predator that deploys different prey-capture methods with different types of prey	Yes	Yes

The predation rate of three spiders of the Salticidae family were also investigated by Weterings *et al.,* (2014) [37] in Southeast Asia. They investigated, in a terrarium, *Plexippus paykulli*, *Plexippus petersi* and *Menemerus bivittatus* the predation rate on the culicid mosquitoes *Armigeres moultoni.* Their results showed a difference in predation rates among the spider species and among sexes. For all species, female spiders fed on significantly more mosquitoes than male spiders. Mosquito density positively affected predation rates, but this effect was small. This observation led researchers to conclude that salticids, particularly *Plexippus* spp, have the potential to be valuable biological control agents for mosquitoes.

Strickman *et al.* (1997) [38] investigated, *Crossopriza lyoni*, family Pholcidae a common inhabitant of homes in the rural villages of Thailand where dengue fever, transmitted by the *Aedes aegypti* mosquito, is endemic. Their laboratory observations showed that spiderlings, after moulting, were capable of overpowering the adult *Aedes aegypti* mosquito many times their own size. They also observed that the spiders' principal means of capturing prey was to throw silk with the aid of the hind legs to immobilize mosquitoes thus entangling them in the standing web. The results of the study suggest that *C. lyoni* could be an important component of integrated control of *Aedes aegypti* and help reduce dengue transmission.

A stochastic event such as the one that occurred in 2010 in the Pakistan village of Sindh could provide a lead to consider spiders as potential candidates in an integrated system of mosquito control. Messenger (2011) [39] and Goswami (2014) [40] report that immediately after the floods, thousands of spiders sought refuge in tall trees, cluttering the leaves and branches with their webs (Figure 2). These massive webs that the spiders had spun were quite effective at catching insects especially mosquitoes. People in Sindh reported fewer cases of malaria which they attributed in part to the spider webs that trapped mosquitoes. However, trees slowly dying was reported as a major drawback after the flood.

[**Source:** https://news.nationalgeographic.com/news/2011/03/pictures/110331-pakistan-flood-spider-trees-webs/] [41]

Fig 2: Trees shrouded in spider webs lining the edges of a submerged farm field in the Pakistani village of Sindh.

Spiders belonging to family Araneidae are exclusively orb-weavers. They are sit-and-wait predators. The basic orb-web structure consist of radial threads. Vibrations caused by a prey insect stumbling across a trip-line are transmitted in such a way that the spider can determine in what direction it must give chase. As soon as any vibrations in the web are felt, they rush near the insect and immobilise them by throwing strands of silk around it [42]. Mohan (2017) [43] observed the long clawed orb weaver spider *Tylorida striata* in India spinning strands of silk around a *Culex* mosquito that had just sucked blood. However, Pollack (2014) [44] points out that many spiders weave webs with spaces between the strands that are just right to catch large insects, but allow smaller ones to fly through. It takes energy and time for the spider to weave the web, and the more threads per unit area, the greater the expenditure. Pollack (2014) [44] concludes that it would not be worth creating a densely-woven web just to catch small prey. If relying upon small insects in the diet were a good economical practice, then it is likely that the spiders would subscribe to that strategy. Jackson and Cross (2015) [36] also explain that while many spiders eat mosquitoes, a spider is not automatically a mosquito specialist if it eats mosquitoes, or even if it primarily eats mosquitoes. Instead, specialization pertains to predators being adaptively fine-tuned to specific types of prey. It is important to keep this basic meaning of specialization conceptually distinct from diet breadth, that is, whether the organism is stenophagous or euryphagous. There is therefore need for further research to find out which species of orb-weaving spiders produce webs which are capable of trapping and feeding on mosquitoes.

Role of spider venom in controlling *Plasmodium*

Not only do spiders help reduce incidents of malaria through preying on larva and adults of mosquitoes but even their venom has also emerged as a promising important pharmacological tool against the malarial parasite [45]. The venom of some spiders have been observed to possess anti-plasmodial activity against the intra-erythrocyte stage of *Plasmodium falciparum*. Pimentel *et al.* (2006) [46] isolated psalmopeotoxin I (PcFK1), a 33-amino-acid residue peptide from the venom of the tarantula spider *Psalmopoeus cambridgei*. They observed that it possessed strong *in vitro* anti-plasmodial activity against the intra-erythrocyte stage of *Plasmodium falciparum.* What they discovered most important was that the peptide did not lyse erythrocytes and was not cytotoxic to nucleated mammalian cells and did not inhibit neuro-muscular function. However, Bannister and Mitchell, (2003) [47] advise that it is not sufficient to predict the target of this peptide in the infected red blood cells, owing to the unusual biology of *P. falciparum* and lack of completely elucidated metabolism and changes in the infected red blood cells. Perhaps it would be important to carry out further investigations to help understand the unique mechanism of action of this peptide and to enhance its utility as a new antimalarial drug against the intra-erythrocyte stage of the malaria parasite.

Recommendations

Arguments have been raised by several researchers in whether spiders will effectively control pest populations in most environments. Limited evidence of their importance is not because they are unimportant but because they have been so poorly studied as biological control agents especially in mosquito infested areas.

Hadole and Vankhede, (2012) [2] advocate for the use of spiders as biological control agents because of the advantages of their high fecundity rate and ease of rearing, handling and transporting. Ooko (2015) [48] further points out that most spiders pose no danger to humans.

Perhaps, it would behove human communities to foster spiders in and around their homes. According to Vijayalakshmi and Ahimaz (1993) [49], the use of spiders as biological control agents has already proved to be a great success in countries like China and Japan. People have to be made aware about the role of spiders in nature and be encouraged to maximally utilise their predatory role to their advantage.

Conclusions

This review has shown that spider predation could be of great ecological significance in suppressing mosquito populations. Management of spider populations could provide the additional control of adult mosquitoes needed to reduce the transmission of mosquito-borne diseases. The question to be asked is on the possibility of utilizing spiders for biological control in, especially throughout Africa and Asia. There is need therefore to develop at different scales, models that incorporate different biological factors for the successful establishment of effective biological control of mosquitoes by spiders. Methods of monitoring effectiveness of control and highlighting and solving potential problems before releases need to be developed. Nyffeler and Benz, (1987) [23] suggest that spiders could become of greater importance, if it were possible to increase the numbers of spiders. This could be possible if participatory forms of knowledge development and sharing are implemented in Integrated Pest Management.

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