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Biodiversity and Conservation of Arthropod Natural Enemies in Tea Plantations of India: An Appraisal

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ABSTRACT

Arthropod natural enemies (predators and parasitoids) play a vital role in controlling the pest population in agricultural systems. But their population is declining rapidly due to some modern agricultural practices like chemical pesticide application demanding more attention to this field. Proper documentation and conservation of these endemic natural enemies in the tea plantations is needed to naturally control the tea pests reducing chemical application. In the present review, natural enemy species recorded from tea plantations of India are listed with an analysis of relative abundance among different families. In addition, some conservation strategies such as modifications of adverse agricultural practices, provision of food and shelters, application of semiochemicals etc are discussed which would help enhancing their population as well as their efficacy in the tea ecosystem. While challenges and future research opportunities in this field are also outlined.

Key words: *Predators, Parasitoids, Food spray, Semiochemical, Biological control, Chemical pesticide*

Introduction

Tea, *Camellia sinensis* (L.) O. Kuntze is an evergreen perennial woody plant that is cultivated for its leaves from which the world's most famous and the cheapest drink is prepared. With suitable climatic conditions and biogeography, India ranks 2nd in the production of this economically important crop. North-East India (Assam; West Bengal-Darjeeling, Dooars and Terai) and southern India (Kerala, Karnataka and Tamil Nadu) are the two major tea growing areas of India. As the tea plantation is done in large contiguous areas as monoculture, it resembles a "single species forest" (Cranham, 1966; Hazarika *et al.,* 2009) with planned biodiversity (Altieri *et al.,* 2004; Hazarika *et al.,* 2009). This forms a relatively stable ecosystem which provides food and a steady microclimate for arthropod communities *i.e.* the pest species and their natural enemies (predator or parasitoid)(Hazarika *et al.,* 2009). The two major Indian tea growing regions have their own distinctive pest species complex due to their different geographic locations. In North-East India, the commonly observed arthropod pests that cause

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extensive damage to the crop are the tea mosquito bug (*Helopeltis theivora* Waterh.), looper caterpillars (*Hyposidra talaca* Walker, *Hyposidra infixaria* Walker and *Buzura suppressaria* Guen.), red spider mite (*Oligonychus coffeae* Nietner), thrips (*Scirtothrips dorsalis* Hood and *Mycterothrips setiventris* (Bagnall)), jassid (*Empoasca flavescens* Fabr.), red slug caterpillar (*Eterusia magnifica* Butl.), flush worm (*Cydia leucostoma* Meyrick), tea tortrix (*Homona coffearia* Nietner), leaf roller (*Caloptelia theivora* Walsingham) and aphid (*Toxoptera aurantii*(Boyer de Fonscolombe)). The dominant arthropod pests observed in the South Indian tea fields are the pink mite (*Acaphylla theae* (Watt)), purple mite (*Calacarus carinatus* (Green)), red spider mite (*Oligonychus coffeae* Nietner), scarlet mite (*Brevipalpus californicus*(Banks)), flush worm (*Cydia leucostoma* Meyrick), leaf roller (*Caloptelia theivora* Walsingham), tea tortrix (*Homona coffearia* Nietner), thrips (*Scirtothrips bispinosus* (Bagnall)), aphid (*Toxoptera aurantii*(Boyer de Fonscolombe)) and shot-hole borer beetle (*Xyleborus fornicatus* Eichhoff). Some minor pests such as mealy bugs, leaf miners, mirids, scale insects, leaf eating lepidopterans are also encountered occasionally (Muraleedharan *et al.,* 1988).

Tea pests are generally controlled by applying easily available synthetic chemical pesticides.These pesticides not only kill the pests but also affect the beneficial arthropod natural enemies which control the rapid growth of the pests naturally. Due to this reason, ill effects of pesticide applications like pest resurgence and secondary pest outbreak occurs. Besides, overuse of pesticides can lead to pesticide resistance, health hazard issues and environmental pollution. Application of Pesticides with selective formulations in reduced dosages in limiting area and time can reduce its harmful effects on the arthropod natural enemies. The population and effectiveness of these natural enemies can also be increased by providing food and shelter along with some modifications in agricultural practices. In this way, biological control of the pests can be achieved by conserving the biological diversity of the arthropod natural enemies which also helps in reducing the pesticide applications. Further, conservation of naturally occurring predators and parasitoids are far better than the introduction of the exotic ones to avoid ecological problems (Brader, 1980).

In the present review, the information on the diversity of natural predator and parasitoids of the tea pests found in the tea plantations of India are compiled together and also some conservation strategies of these arthropod natural enemies are considered for safe pest management.

Diversity of Arthropod Natural Enemy in Tea Plantations of India

In biological control of tea pests, natural enemy diversity has a crucial role in the tea ecosystem (Barthakur, 2011). Arthropod natural enemies are mainly of two types: (a) Predators such as coccinellids, mirids, syrphids, arachnids etc. that kill the pests for food and (b) Parasitoids such as ichneumonids, braconids, eulophids, tachinids etc. that lay eggs on their host and their larvae parasitize it eventually killing the host. Hundreds of arthropod natural enemies were recorded in the tea fields of southern and north-eastern India. Several important predators and parasitoids that have a significant role in naturally controlling the pests in the Indian tea ecosystem are listed in Table 1. The arthropod natural enemies belong to the class Arachnida and Insecta. The arachnids are predatory mites and spiders that belong to different families. Among them Oxyopidae, Salticidae and Phytoseiidae are dominant. Coleoptera, Hemiptera, Diptera, Neuroptera, Thysanoptera and Mantodea are the orders that include predatory insects belonging to different families. Out of these predatory arthropod families, Coccinellidae comprises 29%, Syrphidae 16%, Phytoseiidae 8%, Salticidae 8%, Reduviidae 8%, Lygaeidae 5%, Pentatomidae 5%, Aelothripidae 5%, Oxyopidae 3% and rest of the predatory arthropods 13% (Fig. 1). Parasitoids found in the tea plantations are less in number than the predators. These are included in two insect orders- Hymenoptera and Diptera. Out of the different families of these two orders, Braconidae occupies 25%, Ichneumonidae 21%, Eulophidae 21%, Tachinidae 12%, Aphidiidae 6% and rest of the insect parasitoids 15% (Fig. 2).

The presence of natural enemies in the tea ecosystem appears to be vital as 80% population of red slug caterpillar (*Eterusia magnifica*) is parasitized by Tachinid fly, *Argyrophylax* sp.and upto 47% of looper caterpillars (*Buzura suppressaria, Hyposidra sp.*) is reported to control by *Cotesia sp.* in organic tea gardens (Das *et al.,* 2006). In controlling tea mosquito bug (*Helopeltis theivora*), spiders such as *Oxyopes* sp., *Plexippus* sp., *Phidippus* sp., *Marpissa* sp. and praying mantids, reduviid bugs and chrysopidae lacewings play a significant role (Das *et al.*, 2010; Rahman *et al.*,

2005). A large number of coccinellid beetles such as *Jauravia* sp., *Menochilus* sp., *Coccinella* sp., *Aspidimerus* sp., *Micraspis* sp., *Scymnus* sp. etc. are predatory on flush worm (*Cydia leucostoma*), aphid (*Toxoptera aurantii*), thrips (*Scirtothrips dorsalis, Mycterothrips sentiventris, Lefroyothrips lefroyi*), jassid (*Empoasca flavescens*) and red spider mite (*Oligonychus coffeae*). On an average adult Lygaeidae bug *Geocoris ochropterus* feeds on 13 aphids per day for about 22 days (Mukhopadhyay *et al.,* 2007). Its larvae also feed on tea thrips effectively (Sannigrahi *et al.,* 1992). Adult and larvae of lady bird beetle may consume as many as 50 aphids per day and 300 aphids during its larval development period respectively (Hazarika *et al.*, 2001). Larvae of *Chrysoperla carnea* consume red spider mite eggs and adults (Das *et al.,* 2010) and may feed up to 600 aphids during its developmental period (Hazarika *et al.*, 2001). On an average, *Micraspis discolor* grubs feeds on 188.66 tea aphids and 280.30 red spider mites during its developmental period (Roy *et al.,* 2010). Braconid, Ichneumonid and Eulophid wasps and Tachinid flies play crucial role in controlling looper caterpillars (*Buzura suppressaria, Hyposidra sp.*), flush worm (*Cydia leucostoma*), aphid (*Toxoptera aurantii*), red slug caterpillar (*Eterusia magnifica*), leaf roller (*Caloptelia theivora*) and tea tortrix (*Homona coffearia*) by parasitizing them. There is no report present on the natural enemy of the shot-hole borer beetle (*Xyleborus fornicates*).

Some of the species of predators and parasitoids such as *Scymnus* sp., *Micromus timidus, Aspidimerus circumflexa, Cotesia sp., Argyrophylax* sp. etc are important biological agents as they control more than one pest species in the tea ecosystem. Laboratory rearing of these natural enemies is necessary for their conservation. Scanty reports are present on their culture methods. However, predator of thrips and aphid, *Geocoris ochropterus* was successfully reared on the pupae of the ant *Oecophylla smaragdina* in laboratory (Mukhopadhyay and Sannigrahi, 1993). Rearing of the predator of tea mosquito bug and red slug caterpillar, *Sycanus croceovittatus* was successfully done on termite diet in laboratory (Das and Mukhopadhyay, 2008). Mass rearing of the predator of the looper caterpillar (*H. talaca*), *Sycanus collaris* was also possible on the larvae of rice moth, *Corcyra cephalonica* in laboratory (Sarkar *et al.,* 2019). Different species of *Cotesia*, a good predator of looper caterpillars could be successfully reared in laboratory (Chen *et al.,* 2016; Hill, 1986; Jiang *et al.,* 2004; Kaiser *et al.,* 2017; Khan *et al.,* 2017; Muirhead *et al.,* 2008; Omwega *et al.,* 1997; Patil *et al.,* 2016; Potting *et al.,* 1997; Robert *et al.,* 1992; Sarkar *et al.,* 2020).

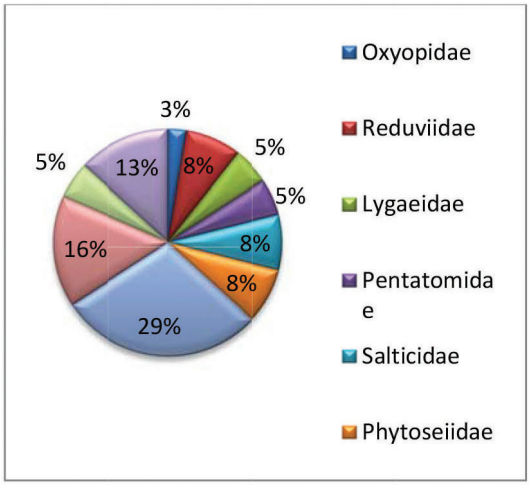

Fig. 1. Relative abundance (%) of different families of predators in Indian tea plantations.

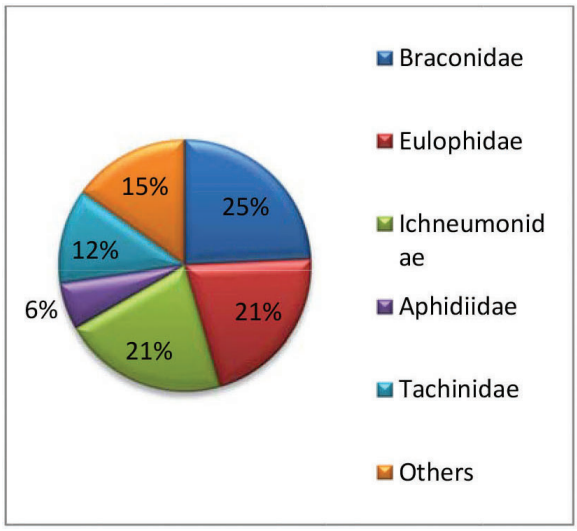

Fig. 2. Relative abundance (%) of different families of parasitoids in Indian tea plantations.

Conservation of Arthropod Natural Enemy

In ecologically complex and stable ecosystems like tea plantations, the role of arthropod natural enemies in controlling tea pests is of great importance. Endemic arthropod natural enemy populations have regulated the most damaging pest population density below outbreak levels for millions of years (Dix *et al.*, 1995). Biological control of the pests can be achieved in crop lands by conserving the natural

Table 1. Tea pests and their natural enemies in India

Pest Species	Natural Enemies	Class: Order: Family	Reference
	PREDATORS		
Tea mosquito bug, *Helopeltis theivora* Waterhouse (Hemiptera: Miridae)	*Sycanus croceovittatus*	Insecta: Hemiptera: Reduviidae	Das *et al.*, 2010
	Chrysoperla carnea	Insecta:Neuroptera: Chrysopidae	Das *et al.*, 2010
	Oxyopes sp.	Arachnida:Acarina: Oxyopidae	Das *et al.*, 2010
	Plexippus sp.	Arachnida:Acarina:Salticidae	Das *et al.*, 2010
	Phidippus sp.	Arachnida:Acarina:Salticidae	Das *et al.*, 2010
	Marpissa sp.	Arachnida:Acarina:Salticidae	Das *et al.*, 2010
	Hierodula sp.	Insecta:Mantodea:Mantidae	Das *et al.*, 2010
	PARASITOIDS		
Looper caterpillars, *Hyposidra talaca* Walker (Lepidoptera: Geometridae)	*Cotesia* sp.	Insecta:Hymenoptera:Braconidae	Das *et al.*, 2010
	Argyrophylax sp.	Insecta:Diptera:Tachinidae	Das *et al.*, 2010
	Sycanus collaris	Insecta: Hemiptera:Reduviidae	Sarkar *et al.*, 2019
	Cotesia sp.	Insecta:Hymenoptera:Braconidae	Das *et al.*, 2010
Hyposidra infixaria Walker (Lepidoptera:Geometridae)	*Cotesia* sp.	Insecta:Hymenoptera:Braconidae	Das *et al.*, 2010
Buzura suppressaria Guen. (Lepidoptera: Geometridae)	*Aphanogmus* sp.	Insecta:Hymenoptera:Ceraphronidae	Das *et al.*, 2010
	PREDATORS		
Flush worm, *Cydia leucostoma* Meyrick (Lepidoptera:Tortricidae)	*Calleida nilgirensis*	Insecta:Coleoptera:Carabidae	Muraleedharan *et al.*, 1988
	Jauravia pubescens	Insecta:Coleoptera:Coccinellidae	Muraleedharan *et al.* ,1988
	Menochilus sexmaculatus	Insecta:Coleoptera:Coccinellidae	Muraleedharan *et al.*, 1988
	Pseudopachybrachius guttus	Insecta:Hemiptera:Lygaeidae	Muraleedharan *et al.*, 1988
	Opistoplatys sp.	Insecta:Hemiptera:Reduviidae	Muraleedharan *et al.*, 1988
	Micromus timidus	Insecta:Neuroptera:Hemerobiidae	Muraleedharan *et al.*, 1988
	PARASITOIDS		
	Goniozus sp.	Insecta:Hymenoptera:Bethylidae	Muraleedharan *et al.*, 1988
	Apanteles aristaeus	Insecta:Hymenoptera:Braconidae	Muraleedharan *et al.*, 1988
	Apanteles coedicius	Insecta:Hymenoptera:Braconidae	Muraleedharan *et al.*, 1988
	Apanteles sp.	Insecta:Hymenoptera:Braconidae	Muraleedharan *et al.*, 1988
	Ascogaster	Insecta:Hymenoptera:Braconidae	Muraleedharan *et al.*, 1988
	Bracon sp.	Insecta:Hymenoptera:Braconidae	Muraleedharan *et al.*, 1988
	Dolichogenidea sp.	Insecta:Hymenoptera:Braconidae	Das *et al.*, 2010
	Fornicia sp.	Insecta :Hymenoptera:Braconidae	Muraleedharan *et al.*,1988
	Asympiesiella sp.	Insecta:Hymenoptera:Eulophidae	Muraleedharan *et al.*,1988
	Elasmus sp.	Insecta:Hymenoptera:Eulophidae	Das *et al.*, 2010
	Nesolynx sp.	Insecta:Hymenoptera:Eulophidae	Das *et al.*, 2010
	Pediobius sp.	Insecta: Hymenoptera:Eulophidae	Das *et al.*, 2010
	Tetrastichus sp.	Insecta:Hymenoptera:Eulophidae	Das *et al.*, 2010

Table 1. *Continued ...*

Pest Species	Natural Enemies	Class: Order: Family	Reference
	Eurytoma sp	Insecta:Hymenoptera:Eurytomidae	Muraleedharan *et al.,* 1988
	Eriborus sp.	Insecta:Hymenoptera:Ichneumonidae	Muraleedharan *et al.,* 1988
	Plectochorus sp.	Insecta:Hymenoptera:Ichneumonidae	Muraleedharan *et al.,* 1988
	Pristomerus sp.	Insecta:Hymenoptera:Ichneumonidae	Muraleedharan *et al.,* 1988
	PREDATORS		
Tea Aphid, *Toxoptera aurantii* (Boyer de Fonscolombe) (Hemiptera:Aphididae)	*Allobaccha nubilipennis*	Insecta:Diptera:Syrphidae	Muraleedharan *et al.,*1988
	Betasyrphus serarius	Insecta:Diptera:Syrphidae	Muraleedharan *et al.,*1988
	Dideopsis aegrota	Insecta:Diptera:Syrphidae	Muraleedharan *et al.,*1988
	Episyrphus baltealus	Insecta:Diptera:Syrphidae	Muraleedharan *et al.,*1988
	Ischiodon sculellaris	Insecta:Diptera:Syrphidae	Muraleedharan *et al.,*1988
	Paragus libialis	Insecta:Diptera:Syrphidae	Muraleedharan *et al.,*1988
	Aspidimerus circumflexa	Insecta:Coleoptera:Coccinellidae	Das *et al.,* 2010
	Coccinella septempunctata	Insecta:Coleoptera:Coccinellidae	Das *et al.,* 2010
	Coccinella transversalis	Insecta:Coleoptera :Coccinellidae	Das *et al.,* 2010
	Jauravia pubescens	Insecta:Coleoptera:Coccinellidae	Muraleedharan *et al.,*1988
	Menochilus sexmaculatus	Insecta:Coleoptera: Coccinellidae	Muraleedharan *et al.,*1988
	Micraspis discolor	Insecta:Coleoptera:Coccinellidae	Das *et al.,* 2010
	Oenopea sexareata	Insecta:Coleoptera:Coccinellidae	Das *et al.,* 2010
	Ola sp.	Insecta:Coleoptera:Coccinellidae	Das *et al.,* 2010
	Scymnus sp.	Insecta:Coleoptera:Coccinellidae	Das *et al.,* 2010
	Geocoris ochropterus	Insecta:Hemiptera:Lygaeidae	Das *et al.,* 2010
	Micromus timidus	Insecta:Neuroptera:Hemerobiidae	Muraleedharan *et al.,* 1988
	PARASITOIDS		
	Aphidius colemani	Insecta:Hymenoptera:Aphidiidae	Muraleedharan *et al.,* 1988
	Lipolexis sculellaris	Insecta:Hymenoptera:Aphidiidae	Muraleedharan *et al.,* 1988
	PREDATORS		
Red slug caterpillar, *Eterusia magnifica* Butler (Lepidoptera: Zygaenidae)	*Sycanus croceovittatus*	Insecta:Hemiptera:Reduviidae	Das *et al.,* 2010
	Canthecona furcellata	Insecta:Hemiptera:Pentatomidae	Das *et al.,* 2010
	Dalpada oculata	Insecta:Hemiptera: Pentatomidae	Das *et al.,* 2010
	PARASITOIDS		
	Cotesia sp.	Insecta:Hymenoptera:Braconidae	Das *et al.,* 2010
	Argyrophylax sp.	Insecta:Diptera:Tachinidae	Das *et al.,* 2010
	Exorista sp.	Insecta:Diptera:Tachinidae	Das *et al.,* 2010
	Peribaea sp.	Insecta:Diptera:Tachinidae	Muraleedharan *et al.,* 1988
	PREDATORS		
Tea leaf roller, *Caloptelia theivora* Walsingham (Lepidoptera: Gracillariidae)	*Cantheconidea furcellata*	Insecta:Hemiptera:Pentatomidae	Muraleedharan *et al.,*1988

Table 1. *Continued ...*

Pest Species	Natural Enemies	Class: Order: Family	Reference
	PARASITOIDS		
	Elasmus sp.	Insecta:Hymenoptera:Eulophidae	Das *et al.*, 2010
	Mestocharella javensis	Insecta:Hymenoptera:Eulophidae	Muraleedharan *et al.*, 1988
	Sympiesis dolichogaster	Insecta:Hymenoptera:Eulophidae	Muraleedharan *et al.*, 1988
	Diadegma sp	Insecta:Hymenoptera:Ichneumonidae	Muraleedharan *et al.*, 1988
	PARASITOIDS		
Tea tortrix,	*Palexorista solennis*	Insecta:Diptera:Tachinidae	Muraleedharan *et al.*, 1988
Homona coffearia Nietner	*Goniozus* sp.	Insecta:Hymenoptera:Bethylidae	Muraleedharan *et al.*, 1988
(Lepidoptera: Tortricidae)	*Apanteles* sp.	Insecta:Hymenoptera:Braconidae	Muraleedharan *et al.*, 1988
	Ascogaster sp.	Insecta:Hymenoptera:Braconidae	Muraleedharan *et al.*, 1988
	Brachymeria lasus	Insecta:Hymenoptera:Chalcididae	Das *et al.*, 2010
	Apophua sp.	Insecta:Hymenoptera:Ichneumonidae	Das *et al.*, 2010
	Phytodietus sp.	Insecta:Hymenoptera:Ichneumonidae	Muraleedharan *et al.*, 1988
	Triclistus sp.	Insecta:Hymenoptera:Ichneumonidae	Muraleedharan *et al.*, 1988
	Telenomus sp.	Insecta:Hymenoptera:Scelionidae	Das *et al.*, 2010
	PREDATORS		
Tea thrips,	*Scymnus* sp.	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
Scirtothrips dorsalis Hood	*Coccinella septempunctata*	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
(Thysanoptera:Thripidae)	*Aspidimerus circumflexa*	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
Mycterothrips sentiventris	*Coccinella septempunctata*	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
(Bagnall)	*Aelothrips intermedius*	Insecta:Thysanoptera:Aelothripidae	Muraleedharan *et al.*, 1988
(Thysanoptera:Thripidae)	*Mymarothrips garuda*	Insecta:Thysanoptera:Aelothripidae	Muraleedharan *et al.*, 1988
Lefroyothrips lefroyi			
(Bagnall) (Thysanoptera:			
Thripidae)			
Scirtothrips bispinosus			
(Bagnall)(Thysanoptera:			
Thripidae)			
	PREDATORS		
Tea jassid,	*Scymnus* sp.	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
Empoasca flavescens Fabr.	*Aspidimerus circumflexa*	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
(Hemiptera:Cicadellidae)			
	PREDATORS		
Red spider mite,	*Jauravia quadrinotata*	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
Oligonychus coffeae Nietner	*Micraspis discolor*	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
(Acarina:Tetranychidae)	*Scymnus* sp.	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
	Stethorus gilvifrons	Insecta:Coleoptera:Coccinellidae	Das *et al.*, 2010
	Micromus timidus	Insecta:Neuroptera:Hemerobiidae	Das *et al.*, 2010

Table 1. *Continued ...*

Pest Species	Natural Enemies	Class: Order: Family	Reference
	PREDATORS		
Pink mite, *Acaphylla theae* (Watt) (Acarina:Eriophyidae)	*Amblyseius deloni*	Arachnida:Acarina:Phytoseiidae	Muraleedharan *et al.*, 1988
	Amblyseius rhabdus	Arachnida:Acarina:Phytoseiidae	Muraleedharan *et al.*, 1988
	PREDATORS		
Purple mite, *Calacarus carinatus* (Green) (Acarina:Eriophyidae)	*Typhlodromus ovalis*	Arachnida:Acarina:Phytoseiidae	Muraleedharan *et al.*, 1988
	PREDATORS		
Scarlet mite, *Brevipalpus californicus* (Banks) (Acarina: Tenuipalpidae)	*Semidalis* sp.	Insecta:Neuroptera:Coniopterygidae	Muraleedharan *et al.*, 1988

enemy diversity. Less diversified areas tend to be more vulnerable to pest outbreaks (Dix *et al.*, 1995). The conservation goal is to enhance the abundance and diversity of the community of arthropod natural enemy in relation to the pest population in the agro-ecosystem. The efficiency of natural enemies depends upon the general favorability, degree of permanence and stability of environmental conditions to a large extent. So the conservation process includes modification of their environment in a way which supports or enhances the growth, survival and reproductive rate of the natural enemies relative to the pests reducing pest problems.Various strategies or practices that manipulate the environment can promote the conservation of natural enemies. The strategies that can potentially enhance the abundance and diversity of arthropod predators and parasitoids in tea ecosystems may be grouped into six categories:

1. Manipulation of unfavorable agricultural practices;
   a. Pesticide use
   b. Clean culture use
   c. Vegetation diversity
   d. Soil management
2. Providing food supply;
   a. Plant based food
   b. Food spray
3. Providing alternate host;
4. Providing shelter and
5. Semiochemical application.

1. Manipulation of unfavorable agricultural practices

The commonly used agricultural practices and cropping patterns of an agro-ecosystem shapes the environmental conditions of natural enemies. The biology and demands of these natural enemies are greatly influenced by the features of the agricultural practices. Some of the practices that adversely affect the natural enemy community are the overuse of pesticides, use of clean culture and less vegetation diversity in the crop landscape.

a. Pesticide use: The most adverse agricultural practice in tea fields is the overuse of broad spectrum chemical pesticides that reduces the effectiveness of predators and parasitoids either by directly killing it or by indirectly influencing its behavior leading to imbalances between population of pest and natural enemy (Van Driesche and Bellows, 1996). Due to the disruption of the pest-enemy balance, pest out-

breaks occur which may be of two types according to the mechanism of its increase: (i) Pest resurgence is the abnormally quick return of a pest to damaging levels after the initial suppression by pesticides as there will be no natural enemies left for their control and (ii) Pest creation (pest upset or secondary pest outbreak) is the occurrence of a pest which is usually not considered as a major one as it is controlled by natural enemies before the application of pesticides.

The harmful effects of pesticides on the natural enemies can be reduced by using physiologically selective pesticides which are relatively harmless to the natural enemies in ecologically selective ways. Ecologically selective methods include usage of reduced dosages of pesticides with selective formulations and materials in time and area limited applications. Reduced mortality of natural enemies as well as adequate pest control can be achieved by lowering the pesticide dosage (Van Driesche and Bellows, 1996). Selective formulations of pesticides may decrease the harmful impacts on natural enemies as in case of systemic pesticides the natural enemies do not come in contact with it as they do not feed on plant saps (Van Driesche and Bellows, 1996). The pesticide treated area should be reduced and also infrequent applications should be made to decrease exposure to natural enemies. Besides, applications of non-persistent materials in times when predators and parasitoids are in protected stages can be done to reduce exposure to them. Moreover, integrated pest management (IPM) strategies should be adapted in the tea fields to minimize pesticide applications to avoid disruption of pest-natural enemy balance.

b. Clean culture use: Clean culture reflects weed free and crop residue free farming practice. This clean culture technique may impact effectiveness of natural enemies as removal of weeds and crop residues from field may eliminate their shelter and supplementary nourishment source. The weeds serve as their alternate hosts and maintain their natural balance in the field. In tea fields, the pruning residues act as overwintering sites for the natural enemies and also the pests residing in the residues can serve as their food source. So to protect the predators and parasitoids clean culture should be avoided as far as possible.

c. Vegetation diversity: Rich vegetation diversity in the tea landscape is necessary for the rich abundance and diversity of natural enemies. Tea plantations intercropped with selected plants and with different edge plants harbors more natural enemies in the field as they provide alternate food and shelters. Trees and flowering shrubs in and around the tea gardens may enhance the populations of spiders, ichneumonids and syrphids as they provide shelter and alternate food like pollen, nectar and alternative host species (Dix *et al.*, 1995; Landis *et al.*, 2000). Chinese tea plantations intercropped with aromatic plants like *Cassia tora* and *Leonurus artemisia* increases the number of natural enemies significantly reducing *Empoasca onukii* population (Zhang *et al.*, 2017). Tea plots in China intercropped with *C. rotundifolia* have lower abundance of Thysanoptera, and Geometridae caterpillars with increased number of predators and parasitoids (Chen *et al.*, 2019). However, selection of right plant species is important rather than the increase of the plant diversity (Wackers and van Rijn, 2012).

d. Soil management: Agricultural practice like tillage can deter the natural enemy efficacy by destroying their dormant stages. But in case of perennial tea plantations, this practice is not in use adding advantage to natural enemy conservation. However, dust build ups should be prevented as it affects the behavior of natural enemies increasing their mortality. Also this problem is not that much prevalent in the humid climate conditions of tea growing regions.

Providing food supply

a. Plant based foods: Nectars and pollens provided by plants can also act as good sources of food for generalist omnivore predator and parasitoids and most of the natural enemies are omnivores feeding on both plant-provided foods and preys (Coll and Guershon, 2002). Some of these omnivores supplement their prey diet with plant based food by increasing their overall fitness. Adults of many parasitoids and syrphids feed on nectar increasing their oviposition, longevity and flight activity (Wackers *et al.*, 2005). Some of them completely depend on plant food source during part of their life cycle, generally the adult stage (Polis and Strong, 1996). Many of the plants considering as weeds serve as the pollen and nectar sources for these natural enemies. These plant species should be identified carefully and their diversity should be maintained in the field to support the natural enemies.

b. Food spray: In the crop areas where natural food resources are not available, artificial or natural food supplements like pollen and nectars can be dusted

or sprayed onto the crop to support the natural enemy population (Wade *et al.*, 2008). Some types of pollens such as *Typha angustifolia* L. pollen are commercially available and these are used for the establishment of different natural enemies (Messelink *et al.*, 2014). But these pollens are expensive as the hand collection of pollen is labor intensive. Further artificial diets like sterilized eggs of some insects have also the potential to enhance natural enemy establishment (Lundgren, 2009). However, selection of food sources should be carefully done so that it would be more suitable for the natural enemies than for the pests. In the near future, development of economical alternative food sources is a major opportunity and challenge for the researchers for the enhancement of natural enemy population (Messelink *et al.*, 2014).

Providing alternate host

By introducing non-crop plants in the field edges that harbor alternative prey or host species which is not considered as the pest of the crop in that particular field, alternative food source would be made available to the natural enemies for their development. This system known as the "banker plant system" is a promising method as it has enormous potential to conserve the natural enemies, if the practical problems like risk of hyperparasitism of parasitized aphids can be overcome (Jacobson, 2011; Messelink *et al.*, 2014; Nagasaka *et al.*, 2010).

Providing shelter

Shelters for natural enemies can be provided artificially or can be enhanced by manipulating border vegetation and ground covers. There are instances of provision of wooden shelters, straw bundles, boxes etc for augmentation of wasps, spiders, lacewings respectively (Van Driesche and Bellows, 1996). The vegetation diversity of the border areas should include banker plants which provide oviposition site and alternate refuge to the natural enemies. The pruning residues on the ground cover of tea fields should not be removed as these may provide shelters and overwintering sites to some natural enemies like phytoseiid predatory mites that controls herbivorous mite population.

Semiochemical application

Semiochemicals are some chemical compounds released by organisms like insects for communication. Behavior of predators and parasitoids can be triggered by using semiochemicals. Sex pheromones or alarm pheromones released by pest species can guide the natural enemy behavior. These pheromones could be extracted and used to attract the natural enemies in large scale to increase their efficacy. However, such volatiles have not been so far used in many crops for the increased efficacy of natural enemies. The attractants can be used in combination with food spray to stimulate oviposition of predators and parasitoids into the target crop (Kunkel and Cottrell, 2007).

Conclusion

The diversity and abundance of arthropod natural enemies in agro-ecosystems like tea ecosystems is very essential as they contribute in natural control of pests. Biological control of the pest is necessary and should get the importance over chemical control due to many hazardous problems of pesticide application. Also the commercial tea with pesticide residues gets less marketing value affecting the national economy. The modern agricultural practices including the pesticide use continuously deteriorate the predator and parasitoid population in the agricultural systems. Therefore, conservation of endemic arthropod natural enemies as a form of conservation of biological control is needed where environmental conditions of the natural enemies are manipulated according to their survival needs.

The first step in the process of natural enemy conservation is the proper identification of the predator and parasitoid species. For that more accurate identification technique, keys and reference collections are needed which is less available due to shortage of arthropod taxonomists and entomologists in India. New researchers should come forward to work in this area to fill up these lacunae.The biodiversity of predators and parasitoids attacking tea pests in India have been listed in this review for the benefits of the upcoming researchers in this area with discussions of some of their conservation strategies. Further research is needed on some area such as (a) identification of plant diversity in and around tea fields that specifically support natural enemies by providing food and shelter to them; (b) development of alternative artificial food sources that particularly assist the natural enemy population; (c) extraction and utilization of semiochemicals to attract and retain the natural enemies in the field and (d) selection and laboratory mass rearing of natural

enemies that are well adapted to the crop so that it can be released in the field in the absence of adequate number of natural enemies to control the pest.

Conservation of biodiversity of natural enemies in the agricultural environment might contribute in maintaining the ecological balance and provide an alternative to chemical control. Different agencies and disciplines working with similar goals should collaborate among them to make the agricultural pest management and production system sustainable and more compatible with nature conservation. Adequate funding should also be granted to such research projects by the administrations.

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