Insect Pests of Tea and Their Management

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Abstract

Globally, 1031 species of arthropods are associated with the intensively managed tea *Camellia sinensis* (L.) O. Kuntze monoculture. All parts of the plant, leaf, stem, root, flower, and seed, are fed upon by at least one pest species, resulting in an 11%–55% loss in yield if left unchecked. There has been heavy use of organosynthetic pesticides since the 1950s to defend the plant against these pests, leading to rapid conversion of innocuous species into pests, development of resistance, and undesirable pesticide residues in made tea. As a result of importer and consumer concerns, pesticide residues have become a major problem for the tea industry. Integrated pest management (IPM) may help to overcome the overuse of pesticides and subsequent residues. We review the advances made in our understanding of the biology and ecology of major insect and mite pests of tea, host plant resistance, cultural practices, biocontrol measures, and need-based application of botanicals and safer pesticides to understand the present status of IPM and to identify future challenges to improvement.

Made tea: refers to processed tea; dried tea leaf granules ready for brewing

Plucking table: refers to the leveled surface of the tea bush underplucking above which the tender shoots are harvested

INTRODUCTION

Tea, *Camellia sinensis* (L.) O. Kuntze, is an intensively managed perennial monoculture crop cultivated on large- and small-scale plantations situated between latitudes 41°N and 16°S. It is grown on over 2.71 million ha in more than 34 countries across Asia, Africa, Latin America, and Oceania to produce 3.22 million metric tons of made tea annually (30; for comprehensive reviews see References 14, 27, 50, 115). The national economy of many of these countries is largely dependent upon its production, and of several constraints that affect production, insect and mite pests (arthropods) are the most damaging, causing on average a 5% to 55% yield loss (68, 83, 90). This loss costs approximately U.S. $500 million to $1 billion (1). In some cases yield loss can be 100% (70).

To defend the tea crop against pests, organosynthetic pesticides are commonly applied. This application is a burden to planters as well as to the environment and can result in a resurgence of primary pests (90) or mite syndrome (23), secondary pest outbreak such as the *Tortrix* outbreak (23), resistance development (53, 90), and environmental contamination, including undesirable residues on made tea (19, 90). Many research institutes around the world are involved in studying the biology and ecology of tea pests and developing suitable techniques for their suppression. With the exception of book chapters (27, 68, 90) there has been no comprehensive review on insect pest management of tea since that written by Cranham (23) in 1966. Here we review advances made on the biology and ecology of major insect and mite pests of tea and the tactics for management, both new and old, as well as identify future research needs.

TEA ECOSYSTEM

Tea is grown within the tropics and subtropics (17) in different types of porous, well-drained, acidic soils (pH 3.3 to 6.0) in diverse agroecological conditions experiencing a wide range of climatic conditions such as temperatures from −12°C to 40°C, annual rainfall from 938 to 6000 mm, radiation intensity from 0.3 to 0.8 cal cm^{-2} min^{-1}, and relative humidity from 30% to 90%. The evergreen and long-lived (over 100 years) tea plantations (11), consisting of genetically diverse cultivars [interplanted with shade trees in Southeast Asia see (27)], provide a relatively steady microclimate and food supply for insect and mite communities. Tea plantations roughly resemble a "single species forest" (23), and insect and mite species are thought to coexist by way of intratree distribution or well-defined stratification/ecological niche formation (9, 11). Natural enemies (NEs) prefer to remain below the plucking table (53). Weeds are a major component of the tea ecosystem and serve as alternative hosts for pests as well as a refuge for NEs (77). Green manures and cover crops are often grown in vacant areas of the tea field, and in some countries tea is intercropped (35) with citrus (43). This kind of planned biodiversity (5) performs ecosystem services beyond tea production, such as nutrient cycling, pest and microclimate regulation, and detoxification of noxious chemicals (plant exudates). Properties and processes involved in the tea ecosystem, in particular the interaction between plants, pests, and NEs as well as linkage between above- and belowground biota (112) and the associated biodiversity (5), as well as human impact and control (58), have not been well researched.

Major Insect and Mite Pests and Their Biology and Nature of Damage

Globally, 1031 arthropod species are associated with tea (21); a small number of pests (about 3%) are common throughout the world. As a result of autochthonous and heterochthonous recruitment and the influence of climate, altitude, nature of cultivation, and age of plantation (10), however, each geographic region may have its own distinctive pest complex (11, 68, 106, 113).

Mirids. Some 41 species of mirids in the genus *Helopeltis* have so far been described in Asia, Australia, and Africa (99). In recent years, two species of *Helopeltis*, *H. schoutedeni* Reuter (Hemiptera: Miridae) and, as earlier predicted (113), *H. theivora* Waterhouse, have become the greatest enemies of tea planters in Africa (83) and Asia (99), causing 55% (83) and 11% to 100% (68) crop loss, respectively.

A mated female *H. theivora* embeds eggs singly inside the tissues of a succulent stem by splitting it open with the ovipositor. She will lay 4 to 10 eggs per day, laying 220 to 224 eggs in her lifetime. Incubation period varies from 4 to 20 days, and the life cycle is completed within 12 to 40 days. The species is multivoltine with many overlapping generations. However, the population peaks from June to September, coinciding with the rainy season (99).

Nymphs and adults suck cell sap from tender stems, young leaves, and buds, forming reddish brown circular feeding punctures 0.29 to 2.51 mm in size. In severe infestations, damaged leaves with 76 to 210 feeding punctures curl upward and desiccate. Initiation of new shoots is prevented due to the death of the stem and may result in total loss of the crop; *H. schoutedeni* causes dieback and stem canker as well (83). Circular feeding punctures become brown to black lesions owing to salivary enzymes, which, in the presence of salivary amino acids, detoxify the defensive chemicals of the host (98). Induction of insect free amino acid binding peptides and incorporating protease/lipase inhibitors into the plant may protect the tea plant and could form the basis for future transgenic research.

Tea tortricids. Among the leaf-feeders, 19 species of tortricids mostly of the genera *Homona* and *Adoxophyes* are economically important pests of tea in Japan, China, India, Sri Lanka, Taiwan, Turkey, Republic of Georgia, Azerbaijan, and Bangladesh (23, 68, 72). Of these, *Adoxophyes honmai* Yasuda (Lepidoptera: Tortricidae) is a major pest of tea in central and southern Japan, whereas *Homona magnanima* Diakonoff (Lepidoptera: Tortricidae) is more prevalent only in southern Japan. *Homona coffearia* Nietner occurs in India, Indonesia, and Sri Lanka; it causes over 50% yield reduction in Sri Lanka (23).

Female *A. honmai* lays oval-shaped egg masses on the undersurface of young tea leaves from which 1.5-mm-long, pale-yellow-colored neonates emerge and disperse individually to construct leaf-webs for feeding on the growing leaves and shoots. They pupate inside the web after completing five to six instars. *H. magnanima* has a seasonal occurrence similar to that of *A. honmai*, with four generations per year in central Japan. No development occurs below 10.3°C, and 417 degree days are required to complete development from egg to adult emergence (72). Such information is necessary to predict the occurrence of the pest and to design management strategies (72).

Shot hole borer. Eight to nine species of scolytids attack tea (11, 68), of which *Xyleborus fornicatus* Eichhoff (Coleoptera: Scolytidae) is the most serious pest in Sri Lanka, causing up to 91% to 100% infestation in the mid-country wet and dry zones (110). The newly emerged females construct galleries in stems 6.35 to 19.05 mm thick and cultivate the ambrosia fungus, *Monacrosporium ambrosium* Gadd & Loos, for raising mycetophagous larvae. Infested stems or shoots are more common in the second year after pruning than in the third year because the wood becomes hard. However, it is still not known if the death of the stem occurs owing to wood rot or to extensive growth of the fungus in the galleries, which may block the xylem and phloem. Future studies should concentrate on the plant-insect-fungus interaction in a physiological context.

The lower development zero (t_{min}) for eggs and pupae of *X. fornicatus* occurred at 15.7°C and 14.9°C, and optimum temperatures (t_{opt}) for the development of these stages were 30.2°C and 31.6°C, respectively (111). This suggests that at an elevation higher than 900 m, the pest will not survive well due to temperatures below the t_{min}. However, this species has expanded its range by establishing in the high-altitude regions, possibly because of a rise in temperature due to global warming (38).

Scurf: discoloration of green leaves due to damage caused by *B. phoenicis*

R_0: net reproductive rate

r_m: innate capacity for increase

Mites. Mites, as a group, are persistent and the most serious pests of tea in almost all tea-producing countries (23). *Tetranychus kanzawai* Kishida (Acarina: Tetranychidae) is important in Japan, China, Taiwan, and the Philippines (45). Likewise, *Brevipalpus phoenicis* (Geijskes) (Acarina: Tenuipalpidae), *Acaphylla theae* (Watt) (Acarina: Eriophyidae), and *Calcarus carinatus* (Green) (Acarina: Eriophyidae) occur in most of the tea-growing Asian and African countries (68, 83, 101). Perhaps the most important mite is the red spider mite (RSM), *Oligonychus coffeae* Nietner (Acarina: Tetranychidae), which was discovered in 1868 in Assam, India (113). This pest is widely distributed in India, Bangladesh, Sri Lanka, Taiwan, Burundi, Kenya, Malawai, Uganda, and Zimbabwe (32).

Nymphs and adults of RSM lacerate cells, producing minute characteristic reddish brown marks on the upper surface of mature leaves, which turn red in severe cases, resulting in crop losses from 17% to 46% (24). High temperatures, dry conditions, and the absence of shade are conducive to outbreak of this pest. The optimal temperature for growth and development is 30°C (26, 32); the lower threshold for development is 10°C, and 232.6 degree days are required to complete the life cycle from egg to egg (32).

Mites inhabiting the upper leaf surface are easily dislodged by heavy rainfall. Leaf temperature and light penetration within tea bushes also influence mite distribution; *O. coffeae* prefers the middle zone of the bush (30 cm below the plucking surface) because of optimum temperatures associated with within-plant shading (9). Hadfield (34) showed that at an ambient temperature of 30°C to 32°C, the upper zone of the tea plant reached 40°C to 45°C, and shading brought it back to ambient levels.

The scarlet mite, *B. phoenicis*, occurs in almost all the tea-growing Asian and African countries, causing crop losses of 13% in Indonesia, 8% to 17% in South India, and 12% in Kenya (83). Eggs are laid on the leaf petiole, at the base of the leaf hair, or inside cracks and crevices of the stem by 3- to 10-day-old females (106). Occasionally females practice thelyotoky. The life cycle is completed in 30 to 60 days. The larvae, nymphs, and adults suck the cell contents from the undersurface of leaves, mainly along the mid-ribs and base of the petiole. Infested leaves have brown scurf followed by splitting of petiole and defoliation (106).

The nymphs and adults of the Kanzawa spider mite suck the cell contents from tea leaves, producing tiny, pale spots or scars. A female lays 2 to 3 eggs per day on the leaves; lifetime fecundity ranges from 40 to 50 eggs. It completes its life cycle within 40 to 41 days and undergoes a seasonal change in habitat. The Kanzawa spider mite is a polyphagous pest. Within the tea ecosystem, it moves from one part of the tea plant to another and can migrate from the tea plant to another host, more particularly to weeds during a different season. Development of the mite is temperature-dependent within 12°C to 37°C; development ceases at 12°C (45). In Japan it undergoes diapause at 18°C or below (101).

Ecology

Understanding the ecology of individual pests, in terms of their response to abiotic (26, 32, 45) and biotic stresses (43), as well as resource acquisition and allocation (9, 11), is essential to the development of integrated pest management (IPM) in tea (23, 27, 68, 70, 90). To date, compared to the applied aspects, research on the ecology of key pest species has not been as complete. Nevertheless, Banerjee (8–12) has provided important information on resource allocation and population fluctuation in RSM, and Sudhakaran and Muraleedharan (95) have constructed a life table for *H. theivora*. This study revealed that the net reproductive rate (R_0), innate capacity for increase (r_m), and doubling time (DT) of the tea mosquito on tea plants are 129.44, 0.12, and 5.62, respectively, which indicated that the pest could reach outbreak levels rapidly. Other areas that need comprehensive studies include population ecology, community ecology, plant-herbivore interactions, food web analyses (116), and the chemical ecology of arthropod-plant interactions in the tea ecosystem.

PEST MANAGEMENT

With the cultivation of crops came pest problems and crop protection (80); the same is true for tea cultivation. The history and evolution of pest management in tea (90) are similar to those described in other crops (58, 60, 62, 76, 80). However, the demand for contaminant-free tea and the need to sustain productivity and quality have led to a movement toward organic tea cultivation, first in Sri Lanka in 1983, followed by India in 1985, and then by Nepal in 1990 (66). As for all agriculture (122), adequate support for research on IPM in the organic tea production system will be required to develop ecologically sound preventative rather than curative practices, as specified by national and international standards formulated by the International Federation of Organic Agriculture Movement (IFOAM); chemical ecology and landscape studies are central to such research.

Monitoring of Pests and Natural Enemies

The pest complex within a region/crop may undergo dynamic changes over space and time; therefore, pest surveillance programs are needed to ascertain pest species and to estimate "their population density, dispersions and dynamics" (80). This may be achieved through regular surveys in the tea-growing regions through sampling using in situ counts (8, 11, 25, 79); jarring (116); D-vac and sweep netting; and light, pheromone (57, 120), yellow pan, and sticky traps (119). NEs are typically sampled by collecting insects through sweep netting, suction, and trapping (102), as well as by in vitro rearing of hosts (95). Biochemical and molecular techniques are available for detection of parasitism, predation, and disease infection (100), which can also be utilized in the tea ecosystem but have not been to date. Advanced techniques, such as use of ultrasonic sensors for cryptic pests (90), IR-photography for aphids, and satellite-based photography, have great promise. The global positioning system (GPS) and geographical information system (GIS) augment surveillance and are presently being used for mapping the spatial distribution of pests in various crops (15) and have potential use in areawide tea pest management programs. Data thus collected may be useful for forecasting pest outbreaks in specific localities. In tea, research on pest outbreak forecasting is still in its infancy.

Jarring: a technique of monitoring/collecting tree-dwelling arthropods by vigorously shaking the tree

ETL: economic threshold level

Determination of Economic Threshold

Crop loss caused by the pest complex either in totality or by individual pests has been reviewed (70). An action threshold for *H. theivora* in Bangladesh was determined through population modeling studies (2). However, studies on economic threshold levels (ETLs) are limited to a few insects mainly from China (47), India (69), Sri Lanka (90), and Malawi (83) and will need to be determined for other key pests where they occur.

Decision Making

At this stage, information is generated mostly from tea fields, "a small ecological unit, in which ecosystem processes are difficult to model and incorporate into decision making" (58). Knowledge of pest identification, biology, population dynamics, and NE is essential for planters when deciding what management practices to undertake (76). That ETL or action or damage thresholds are available for such a small fraction of tea pests shows the inadequacy of the data necessary for decision making and designing pest management programs. Intra- and interspecific competition including interaction with beneficials help researchers to determine if the target pests are really the key pests and to understand the likely impact of adopting a tactic against that on the tea ecosystem. This aspect has generally been neglected in industrialized agriculture including tea

First-phase cultural practices: specific production practices implemented for reducing crop damage, e.g., farm site selection and soil managements

Pruning cycle: the interval of time between successive prunings

Maintenance foliage: all mature leaves, including fish leaves, left on the bush below the plucking surface

cultivation. For biocontrol to become successful, the tea ecosystem will have to be intensively and carefully managed and the activity and population of NE monitored. For example, if the spider/jassid/looper ratio is larger than 1:2, no control measures are needed (53). The key factors that help in decision making in tea pest management are history of the plantation, planter's experience, or presence/absence of the pest as noticed while walking the field either by a scout or a manager.

TACTICS OF INTEGRATED PEST MANAGEMENT

Cultural Practices

First-phase cultural practices are built into the crop production system and are "compatible with natural processes" (122). These are mostly preventative practices, and their manipulation can help keep some pest populations within tolerable limits (70). Tea plantation site selection may influence pest occurrence, but this possibility has not been studied in organic or conventional production systems.

Pruning and plucking. Pruning is an essential agronomic practice implemented in winter for renovating vegetative growth at the expense of reproduction, to increase crop productivity in subsequent years. By adjusting the pruning cycle to occur every two to six years, the effects of pests that attack stems, branches, and maintenance foliage can be minimized or eliminated. This effect has been demonstrated for *X. fornicatus* in Sri Lanka (89) [Sivapalan (90) called it an "escape strategy"], *B. phoenicis* in Kenya (83), and *O. coffeae* in northeast India (25).

Plucking can help control populations of *H. theivora*, *Empoasca onukii* Matsuda (Homoptera: Cicadellidae), *E. flavescens* F., *E. pirisuga* Matsumura, *E. vitis* Gothe (123), *A. honmai*, and *Caloptilia theivora* (Walsingham) (Lepidoptera: Gracillariidae) by removing either eggs deposited in the young stems or larvae present in the young leaves. However, plucking intensity is important; the higher the intensity, the greater the reduction in pest population (86). These insects, along with *Toxoptera aurantii* Boyer de Fonscolombe (Homoptera: Aphididae), *C. carinatus*, and *Lopholeucaspis japonica* Cockerell (Hemiptera: Diaspididae), distribute themselves between the first and the fifth leaf, where leaf removal may affect their population due to an asynchrony between plant phenology and pest emergence. Intensive plucking induces compensatory growth and production of defensive chemicals (mostly phenolics in the shoots), which may affect herbivory (39, 94). This also encourages increased populations of *Trichogramma dendrolimi* Matsumura (Hymenoptera: Trichogrammatidae) (43).

Sanitation and crop refuse destruction. Bush hygiene maintenance may prevent *Glyptotermes dilatatus* Bugnion and Popoff (Isoptera: Kalotermitidae) attacks and save 30% capital loss (91, 92). Weed free cultivation and preventing trespassing of cattle, goat, and other animals from RSM-infested fields reduce its spread. Weeds grow profusely in tea plantations and compete with the crop for nutrition and soil moisture. They also act as alternative hosts for feeding and oviposition and provide shelter for arthropod pests, but may serve as nutrient supplement for beneficials (5, 77). The litter resulting from weeding and pruning is usually left in the field, and the effect of this plant refuse on pests needs to be studied.

Tillage of soils, soil amendments, and fertilizers. In general, the abundance and diversity of arthropod pests and generalist predators, such as spiders, staphylinids, and carabids, are affected by conventional tillage operations (61). Conservation tillage, in addition to aiding soil and water conservation, may improve plant nutrition and health (46, 56, 122), thereby providing protection against herbivores. In tea crops, tillage operations are mostly concerned with land preparation for planting, following which no major operations are undertaken except forking and light hoeing around the tea bushes for fertilization and weeding during the off season. These practices destroy diapausing pests of tea. Tillage practices followed in established tea plantations roughly resemble conservation tillage; however, its implication on IPM in tea has not been evaluated.

The optimal physical, chemical, and biological properties of soils determine the capability of a crop to resist or tolerate insect pests (4). These properties can be manipulated through soil fertility management by way of application of organic amendments/manures (122) such as coconut oil cake, margosa oil cake, well-decomposed refuses of tea, decaffeinated tea waste, well-decomposed poultry manures (90), and green manure [but not fish manure, which induces buildup of *T. kanzawai* through higher deposition of L-arginine (68)].

Balanced N, P, and K levels induce tolerance to *B. phoenicis* and other pests by enhancing vigor of the plant (96, 97), whereas excess N enhances live-wood termite and sucking pest infestations (92, 97). The elements N and K reduce the incidence of *X. fornicatus* due to growth of new tissues as a support bracket (a new callus developed in the stem around the wound in the form of a bracket for strengthening the damaged branch) over the beetle gallery and convert acetate either to saponins or sterol analogues that inhibit pupation, respectively (114). Such induced resistance is of great importance to IPM and needs further study.

Trap crop and shade trees. Studies related to the use of trap crops in tea are scarce. The use of trap crops is based on the principle that more preferred varieties of a cash crop can be grown to reduce damage in less preferred varieties. The more preferred variety not only attracts pests for oviposition and feeding, but serves as a sink for insects or the pathogens they vector (88). A trap crop also manipulates the habitat in an agroecosystem, which can be included under the ecological engineering approaches for the purpose of IPM (33). As such, susceptible tea clones such as Tocklai vegetative clone TV1 to *H. theivora* may be utilized as the trap crop.

During pruning, a few tea bushes in the center may be intentionally left unpruned for a day or two to accumulate *H. theivora* adults, which are then sprayed with hard insecticides to kill the pests (106). This fits well with the concept that trap crop can be used in conjunction with pesticides (122). Likewise, the shade tree *Gliricidia sepium* serves as a diversionary host for *G. dilatatus* (91). There may be several preferred crops to various tea pests to utilize them for the push-pull (22, 55) or stimulo-deterrent diversion (63); a systematic search for these plants is essential.

Shade trees (for commonly used shade trees, see References 14 and 27) are interplanted with tea plants in Bangladesh, India, Sri Lanka, and Indonesia to provide partial shade for regulation of photosynthesis and leaf temperature. However, this creates a microclimate suitable for *Laspeyresia leucostoma* Mayer (Lepidoptera: Eucosmidae), *E. flavescens*, *Glyptotermes* sp., and *H. theivora* but is unsuitable for *O. coffeae* (106). These examples are in agreement with the principle that intercropping with distantly related plant species can encourage generalist herbivores (7, 122), but studies on their effect on specialists are lacking. In general, such plants including weeds in field crops can visually or chemically interfere with specialist herbivores by reducing the resource concentration (84), presumably creating a less favorable habitat. The trees, however, provide refugia for many generalist predators, especially spiders, but more particularly are ideal habitats for birds and small mammals; each shade tree resembles a beetle bank, which is a refugium for predatory beetles, spiders, birds and small mammals usually in the form of a semi-permanent raised strip in a crop field (104). Citrus interplanted with tea in Georgia encourages buildup of indigenous aphidophagous parasitoids to suppress *T. auranti* on tea and *Aphis craccivora* Koch (Hemiptera: Aphididae) on citrus (43).

Water management. Tea needs water in all phases of its growth and in most areas the crop is rain-fed, with rainfall varying from 650 to 6000 mm (14); the crop is highly susceptible to water logging. Water plays a significant role

Clones: genetically identical individuals multiplied through vegetative means from a single plant

TV: Tocklai vegetative

Jat: an Assamese vernacular word meaning pedigree or caste

not only in plant nutrition (14) but also in IPM. For example, inadequate drainage is not only harmful to the tea crop but also creates conditions conducive to the buildup of *O. coffeae*, *H. theivora*, and termites. During periods of water stress, irrigation is provided and mulching is suggested for soil and water conservation as well as for management of *Empoasca* spp. (123).

Mechanical and Physical Methods

Mechanical methods are manual devices utilized for pest suppression, whereas physical methods affect pests or their environment physically. There have only been a few attempts to utilize these methods for tea pest management.

Hand destruction. Collection and destruction of chrysalids of *Buzura suppressaria* Guen. (Lepidoptera: Geometridae), *A. bipunctata*, *Eterusia magnifica* Butler (Lepidoptera: Zygaenidae), and *Orgyia* sp. (Lepidoptera: Lymantriidae) are economical and useful either for small plantations or for plantations with a large labor force. Continuous monitoring of the field for these pests is essential. Termite mounds along with their queens can be excavated and destroyed mechanically.

Barriers. Erecting either physical or chemical barriers could restrict the movement of pests. For example, drainage systems often serve as a physical barrier to restrict migration of *E. magnifica* and *B. suppressaria* under epidemic conditions (106). Barrier spraying against *H. theivora* has been found to be useful (106). Border plantings of *Adhatoda vesica* serve as a barrier for *O. coffeae* (113); its contribution to tea landscape and to beneficials has not been well researched.

Light traps. Light traps are an important component of physical control methods and have significance in tea pest management. In tea fields, black-light traps, the Pest-O-Flash traps that emit near-UV light of 350-nm wave length, or the Jiaduo insect killer lamp are useful for capturing adults of many lepidopterans (82, 106). Factors that could influence the trap catches, such as temperature, rain, moonlight, cloud-cover, shade trees, and landscape, have not been adequately studied in tea crops. Yellow sticky traps and near-UV radiation reflective film have been used successfully in the tea plantations of Japan, China, and Malawai for mass trapping and repelling tea pests, which resulted in a 73% and 79% decrease of tea thrips and tea leafrollers, respectively (119). A vacuum designed to suck insects from tea plants is in use in Japan for reducing tea leafhoppers, whiteflies, thrips, and mites and has met with great success (119). Although these traps are effective for reducing pest population, they equally capture beneficial insects. Designing traps that could discriminate between pests and NEs would certainly increase their importance.

HOST PLANT RESISTANCE

The role of host plant resistance (HPR) and use of elicitors in arthropod pest management have been extensively reviewed (for the role of HPR in organic agriculture see Reference 122). The importance of HPR in tea has long been suspected (113) without understanding the defense mechanisms involved (13). Until the 1990s, little progress was made on selection and breeding of pest-resistant cultivars, because crop improvement programs were focused on high yields and product quality (13, 68).

Significant morphometric and genetic variability exists among tea cultivars (12, 31), to which pests react differentially. For example, Chinese varieties are preferred by tetranychids such as *T. kanzawai* and *O. coffeae* and tenuipalpids such as *B. phoenicis* because of their higher rhodoxanthin and L-arginine content and lower tannin content; whereas, Assam jats, which are attacked by eriophyids such as *A. theae*, have less pubescence, stronger cuticularization on the undersurface, lower stomatal density, and low sugar, but are rich in total antioxidant activity, theamine, gibberellic acid, and caffeine (20, 118). Leaf aspect and structure inhibit insect feeding physically (antibiosis), and biochemicals contribute to antibiosis

(12, 20, 118) and are common features of most of the resistant crops. Thirty TV clones were screened against *O. coffeae* and were grouped into moderately resistant (less than 25% damage and reduced fecundity) and susceptible (more than 50% and high fecundity owing to the presence of more depressions on the upper surface); feeding and oviposition nonpreference may be the mechanisms involved. Depressions may provide shelter and protection from predators because the mite constructs a woven roof over leaf depressions for feeding and resting (85). Similarly, clones with thin cuticles are preferred for development and fecundity. An understanding of specific resistance/susceptible mechanisms with respect to reproduction of mites may help in developing resistant cultivars.

Polyphenol-rich but nitrogen-poor clones are resistant not only to *B. phoenicis* (96) but also to *O. coffeae*; higher catechin, phenylalanine ammonia lyase, and glutamate dehydrogenase contents in these clones are believed to cause this effect (20, 118). The Chinese clone Luxi white, which contains a high polyphenol content (54%) (121), and wild teas rich in caffeine (121) are likely to be resistant to mite attack (96) and can be utilized in mite-resistant cultivar development programs. Phosphorus induces resistance to *T. kanzawai*, suggesting the existence of induced resistance in tea (23).

Leaf structure and texture of clones determine the tolerance level against *E. vitis* and *H. theivora*. Because *Empoasca* spp. suck sap from the phloem, their stylets must traverse the cuticle, upper epidermis, palisade tissue, and spongy mesophyll. Therefore the thickness of palisade tissues, subepidermis, and collenchyma under the main vein has significant negative correlation to leafhopper density in tea; thick, spongy cells physically prevent hoppers from probing the leaf tissues. *Empoasca* spp. feeding may induce the salicyclic acid pathway, the reactive oxygen species pathway, and two jasmonic acid/ethylene-dependent defense signaling pathways; however, these are yet to be discovered in tea. Succulent clones from Assam, India, such as TV-1, TV-9, TV-22, TV-25, and TV-26, are more susceptible to *H. theivora* (99); the reason why is not yet known. However, *H. theivora* infestation led to a decrease in phenylalanine ammonia lyase activity and polyphenol content (18). Understanding not only the mechanisms of resistance but also the identification of resistance-conferring genes and their incorporation into the productive cultivars either through conventional breeding or through genetic engineering (67), as well as describing likely changes in proteomes from insects in response to cultivar switching and insect resistance management, will add new dimensions to the HPR programs in tea. Of course, there are many IPM programs that do not use HPR.

CHEMICAL CONTROL

Therapeutics, botanicals, insect growth regulators (IGRs), and insecticides are other options available for arthropod pest management in tea. In a crop production system, approved insecticides are included under the fourth-phase strategies (use of insecticides, pheromones and repellents as barriers, when other strategies fail) (122).

Botanicals

Recently, Isman (49) reviewed work on botanicals and their uses in pest management. Neem, in various formulations, is recommended against insect and mite pests (90, 106); however, it is not effective against *H. theivora* as *Azadirachta indica* A. Juss. is an alternative host of this insect (99). Other than neem, the majority of information on botanicals is restricted to the laboratory studies (40). Some plant extracts possess significant oviposition deterrence or antifeedant or toxic effects on selected tea pests (40) and may form the basis for future research to develop low-cost formulations suitable for large-scale field application. However, their sustainability, standardization, and regulatory approval may act as barriers for commercialization (49). The same antifeedant should not be used for long periods, as prolonged exposure decreases response among herbivores

EPF: entomopathogenic fungi

(3, 59). For organic tea production, botanicals may play an important role, and they may be considered products in crop-protectant rotations to manage resistance development (49) as well as between pluckings of tea.

Insect Growth Regulator

IGRs mimic insect hormones, such as juvenile hormone (JH) and ecdysone, and thus interfere with normal growth and development. Azadirachtin, an IGR of plant origin, has been used against some pests of tea. Diofenolan, a JH mimic, is effective against scale insects and lepidopteran eggs of tea pests (80). Ecdysone agonists such as tebufenzide, methoxyfenozide, and halofenozide have plant systemic action and are effective against lepidopteran pests and white grubs. Whereas the ecdysone agonists are yet to be evaluated against tea pests, diflubenzuron, teflufenoxuron, and buprofezin show some promise (123). Use of metabolic blockers for inhibiting sterol and fatty acid metabolism has been advocated (90). Mite growth regulators such as clofentezine, diflovidazin, hexithiozox, and etoxazole have been developed for the management of phytophagous mites. However, etoxazole has been used against *Tetranychus* sp. in Japan, and the mite has already developed monogenic resistance against it (16). Many more groups of IGRs may show promise in laboratory trials, but their field efficacy and economics are yet to be evaluated against tea pests.

Attractants and Repellents

The use of attractants in pest management systems can be precise, specific, and ecologically sound. Although the use of attractants against tea pests is not yet popularized, synthetic or natural sex pheromone-based attractants are used for monitoring the population of *C. theivora*, *Adoxophyes* sp. (44, 103), *H. coffearia* (75), and *Ascotis selenaria cretacea* Assc. (Lepidoptera: Geometridae) (78). Synthetic pheromones may play a significant role in organic tea production. Research on repellents against tea pests is still in infancy, as is reflected in the absence of published reports.

Insecticides

At one point, DDT was extensively used for tea pest control (23), which along with other organochlorinated compounds, except endosulfan and dicofol, has now been banned in tea. Presently the most commonly used pesticides for managing different tea pests along with their maximum residue limit are available on the web (**http://www.fao.org/docrep/meeting/003/Y1454e.htm**). Sulfur causes tainting (off flavor) in south India and Sri Lanka; hence, its use has been discontinued there, but it is still in use in northern India. Tea pest control incorporates almost all groups of insecticides, including those with new chemistries such as neonicotinoids, spinosyns, avermectins, pyrazoles, and oxadizines. Extensive use of synthetic pyrethroids (SPs) results in buildup of pink mites. Because SPs kill predators, their use is restricted in tea (68). In addition to dicofol and ethion (23), newer acaricides such as pyridaben, accquinocyle, diafenthiuron, etoxazole, spirodiclofen, and bifenzile are now more widely used.

BIOLOGICAL CONTROL

Natural enemy diversity in the tea ecosystem has a significant role in biological control in tea. Hundreds of NEs have been recorded as parasitoids (various braconids, bethylids, eulophids, ichneumonids, tachinids, and muscids) mostly against lepidopterans (93), predators (coccinellids, syrphids, mirids, phytoseiids, and spiders), and pathogens [entomopathogenic fungi (EPF), entomopathogenic nematodes (EPN), viruses, and bacteria] naturally occurring either from a single species or group of insect/mite pests or in the tea ecosystem. Braconids, coccinellids/phytoseiids, and EPF outnumber other agents of the respective group (1, 43, 71, 102).

Conservation of Natural Enemies

Large-scale indiscriminate application of broad-spectrum organosynthetic insecticides eliminates NEs, as is evident from comparative faunistic studies between organic (with high diversity index and uniformity, and lower dominance and equilibrium) and inorganic (reverse of the organic situation) tea gardens (43, 116). Protection, maintenance, and enhancing efficacy of the existing population of NEs through the use of ecofriendly operations or modification of pesticide practices constitute the main objective of conservation biological control (CBC) (51). Habitat manipulation through intercropping with shade trees and covercropping vacant land constitutes a plant diversification program in tea plantations, which may contribute to the process of CBC, by providing shelter, nectar, pollen (108), and alternative hosts/prey to the NEs (122). As is true for many agroecosystems (5), *Arachis pinoti* Krapovickas y Gregori, a cover crop, increases NEs, especially carabids and ground-dwelling spiders, and reduces pest populations in the tea ecosystem. However, in the tea ecosystem, studies on CBC including artificial food sprays (109), chemical ecology, landscape, economics and CBC as an ecosystem service provider have not been undertaken.

Examples of modification of pesticide practices showed that in those fields where no insecticides were applied, the percentage of egg parasitism was 97% compared with 30% in fields where five sprays were used and with no parasitism in fields where 13 spray applications were used (43). Continuous use of SP insecticides for controlling *T. kanzawai* led to resistant strains of *Amblyseius womersleyi* Schcha (Acarina: Phytoseidae) in Japan; Hiranuma-I and Ide-I populations of *A. womersleyi* became resistant to permethrin (64, 65). Recently, Desneux et al. (29) reviewed the sublethal effects of pesticides on the learning performance, behavior, and neurophysiology of beneficial arthropods including parasitoids and predators and discussed the potential of using sublethal dosages of pesticides in IPM programs. Knowledge of this kind may be useful for combining pesticides and biocontrol agents in a compatible manner to design tea IPM programs.

Price et al.'s (81) hypothesis of acquiring plant fitness through NE has converted bitrophic insect-plant interactions into tritrophic plant-insect-parasite interactions. The plant achieves increased fitness through the release of plant volatiles (synomones) that adult parasitoids/predators exploit as cues for the location of host/prey (54, 105). Such induced tritrophic interactions have been documented in tea geometrid-*Apanteles* sp. (Hymenoptera: Braconidae) involving 2,6-dimethyl-3,7-octadien-3-ol and indole (117), and tea-*E. vitis*-*Chrysopa* sp. (Neuroptera: Chrysopidae)/*Leix axyridis* Pallas (Coleoptera: Coccinellidae)/*Spherophoria menthastri* L. (Diptera: Syrphidae) involving methyl salicylate (37). The aphid honeydew-*Aphidius* sp. (Hymenoptera: Braconidae)/*Coccinella septempunctata* Linn (Coleoptera: Coccinellidae)/*C. sinica* Tjeder/*H. axyridis*/*S. menthastri* interaction is another interesting study (36). Xu et al. (117) showed that the composition of *Apanteles*-attracting volatiles (synomones) emitted from herbivore-damaged tea shoots was different from that of the intact or mechanically damaged tea shoots. Studies on tritrophic interactions have been forthcoming, and these may result in the identification of natural as well as synthetic synomones such as salicylate for enticing NEs into a crop ecosystem and also for activating plant defense genes.

CBC: conservation biological control

Ecosystem service provider: agent/component that contributes to the maintenance of the ecosystem

Introduction, Augmentation, and Colonization of Parasitoids and Predators

In tea, little attention has been paid to classical biocontrol programs, even though tea is an introduced crop in the majority of countries. *Macrocentrus homonae* Nixon (Hymenoptera: Braconidae) was successfully introduced from Java, Indonesia, into Sri Lanka and permanently suppressed *H. coffearia* (23). It provided the impetus to undertake similar attempts at classical biocontrol for mites and *X. fornicatus* in Sri Lanka, but these were not successful (23). These failures may have discouraged further initiation of similar projects elsewhere. It is

GM: genetically modified

necessary to reassess the potential of such programs to be undertaken through international cooperation (43). Augmentation of *M. homonae* and *A. deleoni* Muma and Denmark against tortrix and the scarlet mite has been practiced in Indonesia under an IPM program. Mass production and augmentation of *A. nicholsi* Enat., *T. dendrolimi*, and *Apanteles* spp. suppressed yellow mite, smaller tea tortrix, and tea looper, respectively, in China. In tea, many successful IPM programs include one or two biocontrol agents along with manipulation of cultural practices, HPR, and optimum concentrations of selective pesticides (53, 70, 93).

Propagation and Dissemination of Specific Bacterial, Viral, and Fungal Diseases

Many reviews on bacterial, viral, fungal pathogens and EPNs on tea pests (1, 41, 43, 71) revealed *Bacillus thuringiensis* (Bt) as the most successfully utilized microbial insecticide against lepidopterans and *Agromyza theae* (Bigot) Meij. (Diptera: Agromyzidae) (1, 52). Many studies on formulations to improve persistence and field efficacy of Bt have been published (23, 41). Even though the majority of baculoviruses, such as nuclear polyhedrosis virus and granulosis virus, occur naturally, research to convert them to microbial insecticides for tea pests by evolving suitable techniques for production, standardization, formulation, and application has not progressed well except in Japan (48, 73, 74) and China (43) to some extent.

Many EPF were utilized for management of tea pests in China, India, and Sri Lanka alone or in combination with SP and organophosphorus insecticides (1, 42, 43). Vega et al. (107) have reviewed EPF endophytes and reported *Beauveria bassiana* (Bals.) Vuill. to be endophytic in many plants. Although we (42) have shown *B. bassiana* to be pathogenic to *Helopeltis* and other insects, studies relating to its endophytic characteristic in tea have not been undertaken.

FUTURE CHALLENGES IN TEA PEST MANAGEMENT

The future of tea pest management lies in developing an information-based system in which prevention and therapy are combined to reduce the damage/loss caused by pests. As such, thresholds based on damage/loss will need to be established for many more key pests in the near future. Because commodity value per land area is high in tea, emphasis on prevention may prove to be useful and may include advance planning with respect to the implementation of strategies (122).

Transgenic technology has made it possible to introduce foreign insecticidal proteins such as Bt, trypsin and other proteinase inhibitors, lectins, chitinase, and *rol b* (gene responsible for root hair growth) into plant genomes to confer resistance to insects. The first three have been identified as probable candidates for genetically modified (GM)–tea development programs, and a cultivar UPASI-9 has been engineered with *rol b*, Bt, and chitinase genes (67). Development of molecular markers for identification of pest- and disease-resistant cultivars may form an area of future research. Among phloem feeders, species-specific elicitors induce specific plant defense genes, whereas wound-signaling pathways are activated by chewing. The molecular biology of these mechanisms must be understood in tea before undertaking any genetic engineering work. We suspect that in the future, GM plants will occupy an increasingly large share of tea plantations; the impact of such crops on NE and consumer acceptance must be evaluated as a matter of urgency as well as to follow biosafety regulations strictly.

The theory of biological partnership (87) suggests that arthropods and the tea plant have interacted over millions of years to evolve a diverse array of defensive mechanisms. Some of these may provide yet to be discovered mutual benefits. Because arthropod pests do not occur alone but are present with nematodes, diseases, and weeds (28), research has to take a holistic agroecosystem-based IPM approach. Pheromone technology of pests and NEs, development of GM viruses and pesticide-resistant predators/parasitoids, and ecological/organic farming with the goal of minimizing intervention, as well as regional/national/international cooperation for proper implementation of system-based IPM programs are areas that require increased attention in the future. Economic analysis of such IPM programs is another researchable area, as limited information is available.

CONCLUSION

Tea is a global beverage and the demand for contaminant-free made tea is increasing, resulting in stringent rules on the use of pesticides and maintaining their maximum residue limit standards. A key responsibility of tea growers is to increase the production of toxicant-free made tea per unit area. Understanding of the tea ecosystem is limited, and studies of the pest monitoring techniques are not well developed; however, options available in terms of pest management tactics are plentiful. These include combined use of semiochemicals, HPR, trap crops, and deterrents for manipulating pest behavior to develop IPM or stimulo-deterrent diversionary strategy (6). In this strategy, application of selective pesticides of biological and mineral origin and pheromones may be the last option (122) and a systems approach may give better results. The promise shown by the IPM programs in Sri Lanka (90) and Indonesia, as well as their successes worldwide in agriculture over two decades, has made possible the adoption of IPM in other countries as well.

SUMMARY POINTS

1. Thirty-four countries of Asia, Africa, Latin America, and Oceania, situated between latitudes 41°N and 16°S, produce tea, and the national economy of many of these countries is largely dependent upon its production. Of the many constraints that affect tea production, insect and mite pests play a major role, causing 11% to 55% loss in yield worth U.S. $500 million to $1 billion.
2. Over the past few decades, the application of organosynthetic pesticides has resulted in the resurgence of primary pests, secondary pest outbreaks, and resistance development, as well as the presence of environmental contaminants including residues in made tea. To reduce these problems, IPM tactics have emerged as an alternative solution.
3. Understanding the ecological roles of pests in the tea ecosystem and identifying major determinants of biotic and abiotic factors for their abundance are crucial for framing IPM programs in tea plantations.
4. Various cultural practices and biological, mechanical, and physical approaches have been used in different countries either in isolation or in combination with HPR, need-based application of safer pesticides, botanicals, or biorational approaches for tea pest management.
5. Regular monitoring of tea fields and determining the ideal time to apply an IPM component are crucial for the success of IPM.
6. The application of modern molecular technology has opened a new potential area for developing resistant tea cultivars by introducing insecticidal genes or resistant conferring genes to productive tea clones, monitoring NEs, and developing pesticide-resistant NEs.

7. Understanding the basis of tritrophic interactions of tea, pests, and NEs and developing protocols for mass culturing of selected biocontrol agents are essential for an ecofriendly production system. Ecological/organic farming with the goal of minimizing intervention as well as regional/national/international cooperation for proper implementation of system-based IPM programs are areas that require increased attention.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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122. Discusses various principles and methods of pest management in organic agriculture under the purview of four phases of pest management.