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REVIEW

# *Hyposidra talaca* (Geometridae: Lepidoptera) outbreak in tea gardens: management strategies and future prospects

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**Abstract**
Looper infestation in tea growing region of the sub-Himalayan range poses a severe threat to tea industries that can jeopardize a major player in the nation's economy. Despite undertaking several control measures, their impact has only grown due to climate change and ineffective pest management strategies. This comprehensive review consolidates findings from various published articles, encompassing this pest's ecology, morphology, diversity, their resistance patterns to plant allelochemicals and pesticides, and impact of climate change on the growth and development. The pest's habit and habitat, lifecycles, interactions with the environment, and defensive strategies are being studied thoroughly. This review also underscores the paradoxical issue of shade tree planting in tea plantations, which, while integral for quality tea-leaves, inadvertently fosters pest outbreaks. To address this, the planting of suitable shade trees like *Melia azedarach*, having insect repellent ability has been endorsed. Understanding these factors may result in low-cost maintenance, reduction in crop losses, and improved overall efficiency in pest management. This knowledge facilitates the development of proactive and sustainable pest management strategies, which effectively minimize the emergence, and proliferation of resistance, thereby safeguarding the long-term efficiency of pest management strategies.

**Keywords** Looper · Habitat preferences · Shade trees · Climate change · Biocontrol · Insecticides-resistance

## Introduction

### Present scenario: The tea industry in India

During the nineteenth century when the British started tea plantations in India, commercialization of tea started which soon became a flourishing cash crop. Today, the tea industry is not just a major cash crop but also carries cultural significance. India is the second-largest tea-producing country and fourth-largest tea exporter around the globe (Thangaraj et al. 2019; Niranjan et al 2022) with 10% global export to more than 25 countries (Indian Trade Portal 2023). Russia, UAE, Ukraine, and Kazakhstan are some of the largest importers of tea from India. The tea-growing region in India extends in patches from Himachal Pradesh in the North to Assam and West Bengal in the Northeastern (NE) and Tamil Nadu, Kerala, and Karnataka in South India. The NE part of India comprises of the Assam valley and Cachar region of Assam; Darjeeling, Terai, and Dooars region of West Bengal; lesser-known regions of Himachal Pradesh, Uttarakhand, Arunachal Pradesh, Sikkim, Tripura, Nagaland, and Manipur contribute 86% to the total national production (Niranjan et al. 2022) (Fig. 1). The remaining 14% comes from South India that overall leads to the crop production of 1,374.97 million kg and an overall value of tea exports of around US$ 750.63 million in the year 2022 (Tea Board of India 2023).

The evergreen, perennial, mono-cultured tea bushes have been a stable feeding habitat for many of the destructive herbivores (Hazarika et al. 2009). As a consequence, the pest infestation has become prominent and a major cause hindering tea production, particularly in NE India. Besides, covid-19 pandemic worsened the situation. Some of the common pest management practices in tea gardens involves, manual removal, bush sanitations, pesticides implications, etc. (details in chemical and biological management; and cultural management sections) (Mamun et al. 2014), and all these practices demand a large number

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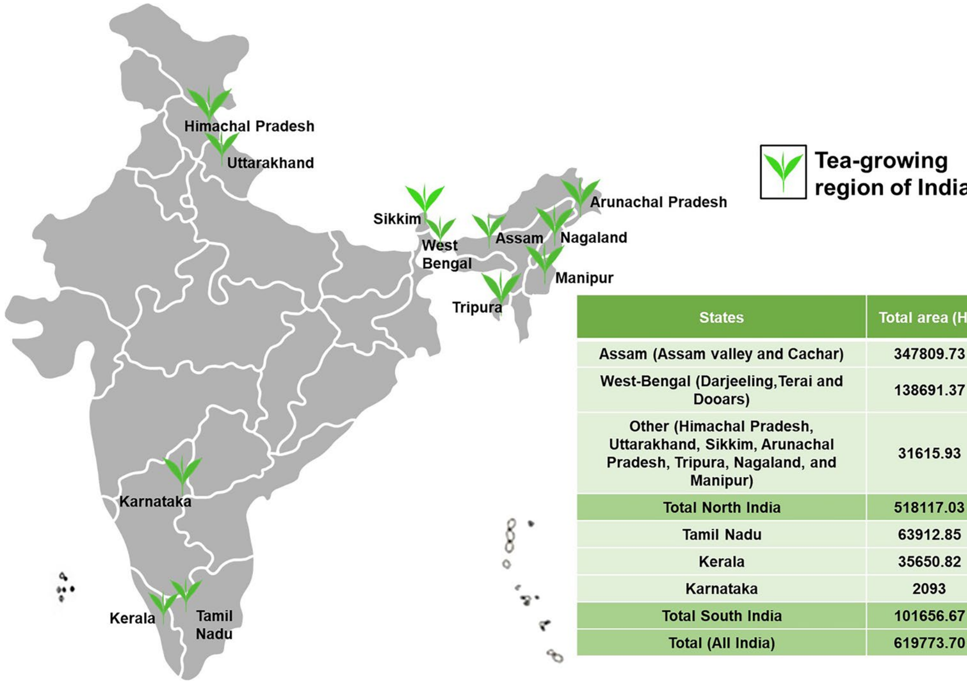


| States | Total area (Ha) | Tea Production in million kg |
|---|---|---|
| Assam (Assam valley and Cachar) | 347809.73 | 698.38 |
| West-Bengal (Darjeeling,Terai and Dooars) | 138691.37 | 418.84 |
| Other (Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Tripura, Nagaland, and Manipur) | 31615.93 | 32.28 |
| Total North India | 518117.03 | 1149.50 |
| Tamil Nadu | 63912.85 | 154.49 |
| Kerala | 35650.82 | 65.98 |
| Karnataka | 2093 | 5.0 |
| Total South India | 101656.67 | 225.47 |
| Total (All India) | 619773.70 | 1374.97 |

**Fig. 1** Tea producing states in India with total area in hectors (Ha) and tea production in million kg during financial year 2022–2023 (Tea Board of India 2023)

of workers. However, due to non-availability of workers during pandemic, most of the tea gardens went untended, especially with regard to pest management. Henceforth, resultant exponential pest population growth resulted in the major destruction of the tea plantations. This situation still remains unsolved and thus is reported often. Recently, rampant attacks of *Hyposidra talaca (H. talaca)*, a voracious defoliator on the tea plantations across West Bengal and Assam have alarmed the tea industries in India (PTI 2023).

*Hyposidra talaca* (Walker) (Lepidoptera: Geometridae), commonly known as "new-looper", also known as black inch-worm, is a polyphagous pest. Tea is one of its preferred hosts. Apart from tea, it has also been reported as a pest of cocoa, cinchona, coffee, litchi, longan, mango, and mangosteen (Kuroko and Lewvanich 1993; Kennedy 1996; Intachat et al. 2001; Sinu et al. 2011; Roy et al. 2017). It is widely distributed in the lowland forests and wild plants of several countries across East and South-East Asia, depicted in the Fig. 2 (Sinu et al. 2011; He et al. 2012; Roy et al. 2017). In India, it is dominated in the NE region of India including West Bengal (Darjeeling, Terai-Dooars), Assam and its adjoining areas like Cachar, Tripura, and Arunachal Pradesh (Basu Majumder 2010; Das and Mukhopadhyay 2008; Das et al. 2010; Sinu et al. 2011; Basu Majumder et al. 2011; Rahman et al. 2007; Nair et al. 2008). Interestingly, there has been no such record of its occurrence in South India (Antony et al. 2011).

Several research works have been done on *H. talaca* on various aspects crucial for its management (Mukhopadhyay et al. 2011; Antony 2012). For instances, studies have delved into the egg-laying patterns highlighting their significance in management practices (Sinu et al. 2013). Additionally, research has investigated the growth, nutritional indices, and digestive enzymes of this pest on both artificial and natural tea diets, providing insights into the insect's dietary preferences and physiological responses (Prasad and Mukhopadhyay 2016). The ecology and management of this pest has been reviewed by Roy et al. (2017), offering a consolidated understanding of the pest's impact on tea plants. Furthermore, Prasad and Roy (2018) investigated the detoxification enzyme profile and total body lipid content of selected lepidopteran pests in Assam's tea plantations contributing valuable information for pest control measures. The insecticide resistance status of *H. talaca* in major tea-growing zones of India has been assessed (Roy et al. 2021) providing critical insights into the effectiveness of current control methods. Moreover, the potential biocontrol agent *Eocanthecona furcellata* has been explored for its role in managing the black inchworm infestation in tea, offering a promising avenue for sustainable pest control practices (Sarkar et al. 2021). Despite, the implementation of various management measures including traditional or chemicals, little success has been achieved in mitigating this pest. Tolerance to pesticides, as well as overlapping broods, became a major hindrance to controlling this looper pest


**Fig. 2** Global distribution of *H. talaca* on the Asian subcontinent including India, China, Japan, Java, Thailand, Malaysia, Papua New Guinea, South Korea, Bangladesh, Taiwan, Nepal, Sri Lanka, Myanmar, Borneo, Philippines and Indonesia. (Sinu et al. 2011; He et al. 2012; Roy et al. 2017)

(Prasad and Mukhopadhyay 2016). Therefore, through a comprehensive study of available literature, the biology and morphology of *H. talaca*, their habitat preferences, and environmental factors favoring this pest outbreak which was further driven by plantations of shade trees have been discussed. Moreover, their adaptive traits and strategies for survival against natural enemies and the toxic effect of pesticides have also been studied and analyzed. Hence, the comprehensive study of these aspects holds great significance for the effective management of this pest.

## Infestation of *Hyposidra talaca* on the Tea bushes of the Northeast Region of India

Tea being a perennial, monoculture plant provides a stable microenvironment and a preferred habitat for several arthropods, nematodes, etc. *H. talaca*, a Geometridae species, which was thought to have expanded from the forest trees and now have become a dominant one in tea plantations (Das et al. 2010; Antony 2012). The first major expansion of *H. talaca* over the tea plantations in the sub-Himalayan region was reportedly observed during 2006–2008 (Sinu et al. 2013). Subsequently, the infestation of *H. talaca* reached a severe level by 2011, leading to a substantial decrease in tea production in the NE region of India (Basu Majumder and Ghosh 2004; Das and Mukhopadhyay 2008; Nair et al. 2008; Hazarika et al. 2009). Until then, only *Buzura suppressaria* Guenee (Lepidoptera: Geometridae) was prominent in the region since 1903 (Sinu et al. 2013). Currently, the activity of this species has increased considerably and expanded to almost every tea garden in the NE India just within 5 – 6 years, with climate change and habitat destruction being determined as the major reasons (Antony 2012).

## Taxonomy and classification of the pest

*Hyposidra talaca* Walker 1860 (Lepidoptera: Geometridae), was first described by Francis Walker in 1860. It belongs to the family Geometridae under the order Lepidoptera of Class Insecta and has been classified by several synonyms including *Chizalade ceptatura* Walker, 1860; *Chizalade cipiens* Walker, 1860; *Lagyra rigusaria* Walker, 1862; *Lagyra bombycaria* Walker, 1866; *Hyposidra vampyraria* Snellen, 1880; *Lagyra myciterna* Druce, 1888; *Lagyra flaccida* Lucas, 1894; *Hyposidra khasiana* Warren, 1894; *Hyposidra grisea* Warren, 1902. However, the currently validated name is *Hyposidra talaca* Walker, 1860.

## Morphology, anatomy, and life cycle of the pest

The looper pest has gained considerable importance as a voracious defoliator in NE India since the last decade. The whole life cycle of the pest with its associated damage symptoms has been depicted in Fig. 3.The adult male and female can easily be distinguished morphologically based on their body sizes, wings pattern, and antennae. Males are smaller than females, have hairy palpi that are reaching beyond the frons, antennae are bipectinated, grey in color, and without a distinct sub-marginal notch in the forewings. While females are larger, 3 times heavier than males, possess filiform antennae, and wings are 1.5 times wider than males, the body is dark fuscous suffused with grey-colored, wavy dark semi-circular patches and distinct sub-marginal notch in the forewings (Das et al. 2010; Anonymous 2024). This pest undergoes complete metamorphosis starting with the eggs, larva, pupa, and then adult. The adult female lays 200–500 eggs per lifecycle and generally prefers laying eggs at a height of 0.02—7.2 m from the ground to favor the dispersion of neonate looper with less predation risk (Sinu et al. 2013). The incubation period is of 6–9 days (Das et al. 2010). Looper has around 4–6 instars stages (Das et al. 2010) which are considered to be the most destructive as they are voracious feeders. Some of the early instar larvae, immediately after hatching, move up in the shade trees and complete their early developmental stage in the shade trees while most of them disperse down to the tea plantation from the shades trees by hanging or swinging with the help of the salivary thread (Sinu et al. 2013). The first three instars are black with seven transverse white stripes. The 4th instar caterpillars are black to dark brown with seven stripes. The 5th instar is dark to light brown, with minute black spots present dorsally (Roy et al. 2017). Pupation takes place in the soil generally around the collar region of tea bushes and shade trees or in the cracks and crevices of the bushes (Sinu et al. 2013). The pupa is blackish brown, with characteristic anal process. It generally undergoes 6–8 generations a year without diapause (Mukhopadhyay et al. 2011) which makes them an incessant pest of tea plantation.

## Habitat preferences and host range expansion

*Hyposidra talaca* is polyphagous by nature (Robinson et al. 2010) having great potential to adapt to different host plants (Robinson et al. 2010; Das and Mukhopadhyay 2014). Till now, more than a hundred alternate host plants have been recorded for this pest which includes forest trees, shade trees, weeds, etc. out of which, around 23 host plants were identified from the Terai-Dooars region of NE India (Basu Majumder and Ghosh 2004; Basu et al. 2010). Several thoughts were suggested on its ancestral habitat. Some reported the pest expansion from Sal dominant forest (Intachat et al. 2001; David and Ananthakrishnan 2004; Sen-Sharma and Thakur 2008; Sinu et al. 2013), while others directed toward the *Schima wallichii* forest. However, the expansion from the Sal-dominant forest was widely accepted, and considered as an ancestral habitat

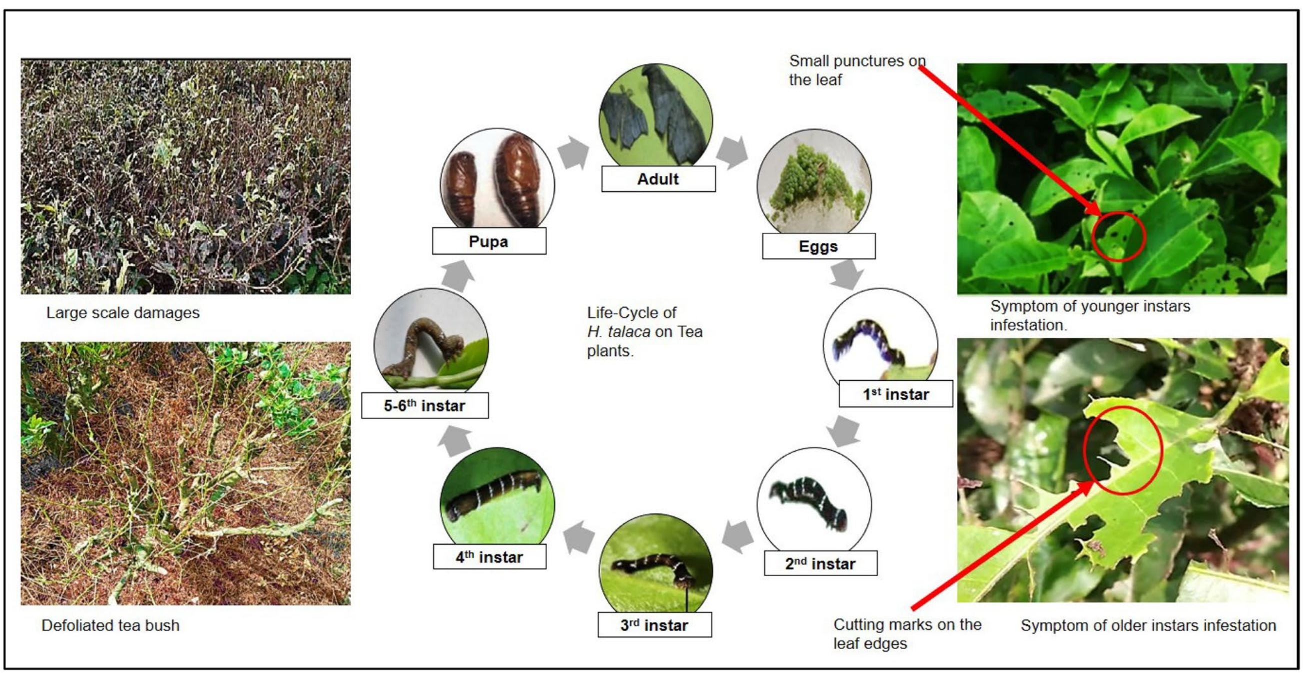


**Fig. 3** Life cycle of *H. talaca* on tea plant and the damage symptom on the leaves (Roy et al. 2017)

while tea was categorized as a derived habitat of this pest (Intachat et al. 2001; David and Ananthakrishnan 2004; Sen-Sharma and Thakur 2008). Furthermore, all the published literature indicates the common reason for its expansion i.e.,'habitat destruction' primarily for tea cultivation that leads to this shifting host situation. Insects often switch to new host plants for various reasons, which includes the greater food supply, potentially leading to improved fitness and reproductive success, and differences in quality of the food that can affect the growth, survival and overall health of the insect larvae. Insects may also choose a new host plant to protect themselves from their natural enemies, such as predators or parasites. Scientific studies have found that lepidopteran insects, including butterflies and moths, are capable of acquiring food preferences through a learning process (Bernays and Wrubel 1985). This preference induction was typically observed after the insects spent one or more developmental stages on a particular host plant. For example, experiment on *Manduca sexta* by De Boer and Hanson (1984) clearly demonstrated the feeding preferences induction on the larvae of this moth to few solanaceous plants which became their preferred host plants. Similar kind of results were also observed on gypsy moth *Lymantria dispar* (Barbosa et al. 1979). Therefore, it may be instrumental for the looper pest as well, since they complete their life cycle in more than one host but prefer feeding specially on the tea plants. Furthermore, empirical evidence suggests that the feeding preferences of lepidopteran insects can modulated by their previous experiences with diverse host plants (De Boer and Hanson 1984). A comprehensive study done by Prasad et al. (2013) and another by Das and Mukhopadhyay (2014) compared the growth and development of looper in tea plants and other host plants. The studies found that the looper was highly benefitted by selecting tea as its new habitat. Moreover, the studies also found that tea-reared *H. talaca* exhibited higher morphological parameters, such as maximum larval weight gain in the final instar, pupal weight, and adult weight, compared to the other host plants. Pupal weight serves as an indirect yet easily measurable indicator of fitness in lepidopteran insects (Leuck and Perkins 1972). The production of eggs in insects is typically supported by nutrients obtained during the larval phase (Telang et al. 2001). In addition, Dadd (1985), has also reported a deficiency of linolenic acid in diet can lead to the failure in the normal growth and development of lepidopterans. This might be the case in tea plant infestations, as tea leaves contain a sufficient amount of linolenic acids and linoleic acids that can be utilized by the pest as a precursor for the production of pheromones and other metabolites necessary for the growth and development of the pest (Prasad and Mukhopadhyay 2016). Consequently, all this host preference phenomena has led to the higher infestation cases and production decline in the tea-cultivated region of NE India.

## Environmental factors favoring pest outbreak

*Rise in temperature*: Being ectothermic in nature, temperature is the single most important environmental factor that directly influences the pest's growth and development, reproductive potential, feeding rate, distribution pattern, behavior, as well as relationship between pests, the environment, and the natural enemies (Prakash et al. 2014; Roy et al. 2017). For instance, ambient temperature (25–30°C) elevation has affected the gypsy moth by decreasing its development time and increasing its survival rate (Williams et al. 2003). Over the last few decades, the entire NE India has been experiencing extreme fluctuations in the weather pattern in terms of decreasing rainfall (6%–8% from the normal) and increased average temperature of around 1.3°C (Roy et al. 2020). Insect physiology is very sensitive to changes in temperature, and their metabolic rate tends to approximately double with an increase in 10°C (Stange et al. 2010; Peck 2016; Skendzic et al. 2021). Similar kind of activities were observed on *H. talaca* where it remains more active under warmer conditions. It leads to an increase in their metabolic rate, as reported by Antony (2012). This heightened metabolic rate results in insects feeding more on plants, and if one type of vegetation is insufficient, they are compelled to feed on different plants to meet their requirements. Rise in temperature elevated consumption rates and therefore decrease the time to pupation, making them less apparent to natural enemies and in some cases increases the potential number of generations per season, which might be the reason for having additional generation of *H. talaca* in the Tarai-Dooars of West Bengal. Furthermore, it has been estimated that with a 2°C temperature increase, insects might experience 1–5 additional lifecycles per season (Yamamura and Kiritani 1998). Besides, lower winter mortality of *H. talaca* due to warmer winter temperatures has also played a significant role in increasing its population (Harrington et al. 2001).

*Decrease in annual rainfall pattern*: The NE India, which normally receives heavy rainfall during the monsoon months (June–September), has changed its character for the worse (Mukhopadhyay and Roy 2008; Roy et al. 2020). The rain comes in quick bursts and floods the region, followed by elongated dry periods. This condition has favored the insects in several ways that include:

i) Dry climates may provide suitable environmental conditions for the development and growth of herbivorous insects (Mattson et al. 1987)
ii) Drought-stressed plants attract some insect species. For example, the ultrasonic acoustic emissions caused by the breaking of water columns in the xylems during

transpiration can invite harmful bark beetles (Halter 2011).

iii) Most importantly, plants stressed by drought are more susceptible to insect attack because of a decrease in the production of secondary metabolites that have a defense function (Yihdego et al. 2019). This might be the case for extensive growth of this newly emerged pest that is causing this overtake of the tea-growing region within such short periods of time.

*Increased $CO_2$ concentration*: Elevated concentrations of atmospheric $CO_2$ concentration can affect the distribution, abundance, and performance of herbivorous insects (Johnson et al. 2020). Such increases can affect consumption rates, growth rates, fecundity, and population densities of insect pests (Tonnang et al. 2022). Further, it was speculated that, tea being a C3 plant, may show higher productivity at elevated $CO_2$ conditions due to increased photosynthesis and respiration activity in the tea plants (Ahammed et al. 2020; Jayasinghe et al. 2021). This, in addition, provides a feeding habitat for *H. talaca* throughout the year resulting in increased pest infestation. Moreover, Ahammed et al. (2020), has also mentioned the decreasing level of defensive allelochemicals in the tea plants due to elevated $CO_2$ level (Li et al. 2019) that further supports the growth and development of *H. talaca* on the tea plants.

## Shade trees enhance pest infestation

Unlike many other parts of the world, tea in NE India is cultivated under the shade of several woody trees, especially leguminous ones (Barua 1994). Shade trees are recommended for tea plants especially in plains as they regulate the proper balancing of the sunrays required to maintain the leaf temperature and humidity optimum for photosynthesis (Antony 2012) for the production of better quality tea leaves. The presence of a large number of alternative host plants has aggravated the looper problem in most of the areas of Assam and West Bengal. A study has confirmed that lepidopteran pest attack is more in shaded tea plantations than in unshaded tea plantations (Sinu et al. 2013). Many new pest outbreaks occur in the tea plantations that are facilitated by the shade trees. Looper pest is one of them. Scales of the shade tree were the exclusive oviposition sites of adult females and the foliage of the shade trees was the alternate preferred feeding host of the larvae of *H. talaca* in tea plantations of NE India. Herbivores insect pests choose the egg-laying sites based on the quality of the plants (Price 1994; Tammaru et al. 1995; Floater and Zalucki 2000). However, the looper pest prefer shade trees as they can provide protecting scales or bark under which the pest can lay their eggs safely away from their natural enemies (Cunningham et al. 2001; Tanhuanpaa et al. 2003). In an experiment with 49 shade trees on the tea plantation by Sinu et al. (2013), it was observed that the most preferred host of *H. talaca* for oviposition and feeding among shade trees were *Acacia catechu, Acacia nilotica, Albizia procera, Bombax ceiba, Toona ciliata, Ficus tinctoria* ssp. *gibbosa, Ricinus communis* except for neem tree *Melia azedarach.* Similarly, GC–MS based investigation done by Ghosh et al (2021) has also reported the presence of insects attractant metabolites such as Caryophyllene, epoxide, Dehydro-beta-ionone, Methyl palmitate, Phytol, etc. in the leaves and bark of *Albizia* sp. that might attract the insects like moth, beetle, whitefly, spider mite etc. which had further promoted pest infestation in the tea field. Therefore, habitat loss and climate change could be the fundamental reason for the primary invasion of looper into the tea ecosystem. However, increased plantation of shade trees have accelerated the invasion by providing a suitable micro-climatic condition optimum for the moth survival in natural conditions. Therefore, a comprehensive study on the habitat utilization of shade trees by this pest particularly for oviposition can help manage pest outbreaks by disrupting egg distributions to prevent their population expansions.

## Impact assessment of *H. talaca* on tea plantation

*Tea Production*: The early instars larva feeds on the tender leaves by making pin hole on the leaves (Basu Majumder and Ghosh 2004; Basu Majumder 2010), while the 4–6th instars looper caterpillars are voracious feeders, and feed on the mature leaves. In extreme cases, it even feeds on the bark of the tea plants causing total defoliation of the tea bushes. It has been reported that a later-stage caterpillar feeds 4 times more than that of the earlier one (Prasad and Mukhopadhyay 2013) and may consume on an average 12,690.33 $cm^2$ of harvestable leaf area and 66.67 g of dry mass of tea leaves during its development (Prasad and Mukhopadhyay 2013). Antony (2012) also reported the consumptions of 4–5 young leaves within 3 h by single larva. Thus, this folivorous pest leads to severe crop loss throughout the year by defoliating the plants as well as hindering the growth of the plants because of feeding on mature leaves leading to loss of metabolic capacity.

*Quality of tea*: Plants produce secondary metabolites mainly to protect themselves from various abiotic and biotic stressors (Fraenkel 1959; Coley et al. 1985). Tea has antioxidant, anti-inflammatory, cardio protective, and stimulant properties, which were determined by the level of polyphenolic catechin and methyl xanthine. These molecules determine the functional quality of this beverage. Changes in tea plant metabolites such as methylxanthines, phenolics, and volatiles, which function as anti-herbivory, can impact several aspects of processed tea quality including flavor, aroma, appearance, and concentrations of health-beneficial compounds (Scott and Orians 2018). For example, Caffeine is thought to have evolved as an anti-herbivore defense and acts as a repellant and toxicant to insects and other herbivorous pests (Hollingsworth et al. 2003; Kim et al. 2011), and variation in caffeine content is associated with pest resistance in tea (Hewavitharanage et al. 1999). Further, Ahmed et al. (2019), in their review also mentioned that the increased level of tea secondary metabolites due to herbivory can directly affect the tea quality. Herbivory can either decrease or increase the production of catechins (Chakraborty and Chakraborty 2005; Dong et al. 2011) or volatiles (Han and Chen 2002; Dong et al. 2011) in tea plants. Han and Chen (2002) found that tea aphid-damaged tea shoots showed the presence of volatile compounds benzaldehyde and (E)-2-hexenoic acid which favorably contribute to aroma. However based on the published literature, evidence for chewing herbivory affecting quality is very limited. That might be because damaged leaves are avoided at the time of harvesting (Scott and Orians 2018). However, Dong et al. (2011) showed that exposing undamaged tea leaves to volatiles released by damaged tea leaves resulted in metabolomic changes in the undamaged leaves. Additionally, Cai et al. (2012) observed continued production of volatiles by weevil-damaged leaves after herbivore removal. Therefore, chewing herbivore damage may result in systemic induction and the induction of defenses that lasts through time that affects the quality of non-damaged leaves.

*Economy*: With a rich history spanning 185 years, tea is a vital component of the country's economy. Indian tea industries is among the oldest and the biggest in the world. This industry serves as a source of employment for over 3 million individuals and exerts a substantial influence on India's foreign exchange earnings (Nair et al. 2023). The economy flourished with the production of good quality tea-leaves. Over the past few decades, tea planters have been facing unsettling situations due to the emergence of a severe attack of tea defoliators mostly looper pest (Das et al. 2010; Sinu et al. 2011; Roy et al. 2017), which leads to the rapid devastation of the tea plantation interrupting production cycle and supply chain. This subsequently causes a decline in exports and a reduction in global competitiveness. A noticeable tea exports declination was recorded from a peak of 252 million kg in 2019 to a mere 51.17 million kg in 2022 with an estimated annual crop loss of around 147 million kg and a revenue loss of around Rs. 2,865 crores in the year 2022 (PTI 2023).

## Chemical and biological management

*Chemical control*: The application of synthetic pesticides has been limited to a few due to the maximum residue limits (MRLs) value for the tea plantation declared by the Food Safety and Standards Authority of India (FSSAI), the European Union (EU), the FAO Codex, Codex Alimentarius Commission and the Environmental Protection Agency of the USA. The Tea Board of India has recommended some synthetic pesticides like deltamethrin (Pyrethroids), quinalphos (Organophosphates), emamectin benzoate (Avermectins), and flubendiamide (Diamides) for controlling looper pest (Prasad and Roy 2018; Plant Protection Code 2024). Additionally, insect growth regulators, such as diflubenzuron are also a potential pesticide to suppress *H. talaca* populations (Basu Majumder et al. 2010, 2012). Unfortunately, synthetic pesticides like organophosphates at the field recommended dose have been found to decrease the population of natural enemies (Sarkar et al. 2021). However, due to overexposure to the toxicants for a longer period has made this pest resistant to the above-mentioned insecticides which became a rising concern for the tea industry (Roy et al. 2017; Saha 2016).

*Biocontrol*: Regular use of synthetic pesticides had severely affected the environment and human health (Mobed et al. 1992). Therefore, to minimize their use and further mitigate their negative impact, the use of biocontrol agents (natural enemies, parasitoids, microbes, etc.) has been adopted which has proven to be the most feasible and economic tool to manage pests (Gillespie et al. 2000). The investigation of naturally occurring parasitoids and predators for the management of this species on tea is still ongoing. Besides, more than 170 species of such natural enemies have been documented from the tea estates of India (Mamun et al. 2010). The stinkbug, *Ecocanthecona furcellata* (Wolff) (Hemiptera: Pentatomidae) (Das et al. 2010), has gained much attention in the context of biological control management. It has been widely studied for its potential in controlling lepidopteran pests across various crops (Chakravarty et al. 2017; Lenin and Rajan 2016; Suyal et al. 2018; Keerthi et al. 2020). Additionally, Sarkar et al. (2021); Sinu et al. (2011) also reported the effectiveness of *Ecocanthecona furcellata* as well as an ant, *Tetraponera rufonigra* (Jerdon) (Hymenop tera: Formicidae) as predators against *H. talaca*. Furthermore, three parasitoids, *Exorista deligata* (Diptera: Tachinidae), *Cotesia* sp. (Hymenoptera: Braconidae) and *Argyrophylax* sp. (Diptera: Tachynidae) have also been found to parasitize on the caterpillars of *H. talaca* (Das et al. 2010; Sharma et al. 2023). Among the predators around 38 avian species such as *Gracupica contra* (L.), *Sturnia malabarica* (Gmelin), *Acridotheres fuscus* (Wagler), common bulbul, *Pycnonotus cafer* (L.), *Gracupica contra* (L.) (Passeriformes:Sturnidae), *Sturnia malabarica* (Gmelin) (Passeriformes: Sturnidae), *Acridotheres fuscus* (Wagler) (Passeriformes: Sturnidae) and *Pycnonotus cafer* (L.) (Passeriformes: Pycnonotidae), etc. were also observed to predate on the caterpillars of *H. talaca* (Sinu 2011). In addition, some pathogenic bacteria like *Bacillus* *thuringiensis varkurstaki* (Bt) and nucleopolyhedrovirus (NPVs) carries dose-dependent potential against looper pest and were recorded to suppress 50–67% of their population in the field (Basu Majumder 2010; Mukhopadhyay et al. 2011; Basu Majumder et al. 2012).

The utilization of plant extracts of *Azadirachta indica* against *H. talaca* has been documented in the study conducted by Basu Majumder et al. (2012). Additionally, water extracts of some tropical plants, namely *Argyreia speciosa, Annona squamosa, Clerodendrum viscosum, Polygonum hydropiper, and Leucas aspera* have also been found to have fatal impact on *H. talaca* (Roy et al. 2015).

## Cultural management practices

On the basis of the existing literature (Basu Majumder 2010; Sinu et al. 2011; Mamun and Ahmed 2011; Roy et al. 2017), the most common cultural practices for *H. talaca* infestation management involves the manual removal of caterpillars and moths, particularly during cold weather while chrysalids were collected from the soil around tea plants. Pupation sites, such as cracks in old tea bushes, were targeted, and bush sanitation, including alkaline wash after pruning, were implemented to minimize looper attacks in the next season. Eggs clustered in bark cracks of shade trees, could be removed by scraping bark, removing moss, and applying lime wash up to a height of 6 m. Egg burning on shade tree trunks and application of insecticide effectively were also performed to reduce egg deposition during peak egg laying seasons (November to March). Due to the polyphagous nature of caterpillars, weed cleaning around tea sections is deemed essential, and the installation of light traps in a 10 ha area were implemented for attracting and collecting moths.

## Traits and strategies adopted by *H. talaca* for survival against natural enemies and the toxic effect of pesticides

*Behavioral adaptation*: One of the major reasons for the survivability of insect pests is that they evolve through rapid adaptation because of selective pressure applied by the changing environmental conditions, shifting habitat, and anthropogenic activity like the application of pesticides and chemicals to prevent pest infestations. Therefore, to survive through this environmental and anthropogenic stress, pests have undergone several behavioral adaptations to avoid or reduce their impact on the fitness of the pest. Moreover, behavioral adaptation is required to expand the host range in polyphagous insects for mating, ovipositing, and foraging (Wiklund 1975; Thomas et al. 1987; Henniges-Janssen et al. 2011). The interesting experiment conducted by Sinu et al. (2011) on the behavioral responses of the pest against the different stimuli of the predators (natural enemies like wasps) has found that *H. talaca* responds to each of the responses differently. They noticed that the caterpillar drop-down acquired U and S-shaped positions in the foliage with the help of the salivary thread as a response to the buzzing sound of the predator wasp (Fig. 5a) (Sinu et al. 2011). Caterpillars dropped and remained motionless to a non-potential predator-like stimulus (mechanical vibration). In bird-active tea plants, around 63% of the caterpillars dropped, and the remaining 37% assumed a deimatic posture in the foliage. The study finds that predatory wasps are the most important insect predator of *H. talaca* caterpillars. Predatory ants like *Tetraponera rufonigra*, although known to influence the herbivory of geometrid caterpillars (Ito and Higashi 1991), had little impact on the pest due to the dropping behavior of *H. talaca* caterpillars. Similar kinds of behavioral responses were also reported from several other pests to escape from potential predators (Floater and Zalucki 2000; Sinu et al. 2007; Azerefegne and Solbreck 2010). Besides, concealed eggs underneath the barks and crevices of shade trees (Fig. 5b) and embedded pupae under the soil (Fig. 5c) to escape from predators are other behavioral characteristics adopted by *H. talaca* for survival (Raymond et al. 2002; Tanhuanpaa et al. 2003).

*Melanism in H. talaca*: Melanism is one of the recently noticed adaptive characteristics in *H. talaca* and was first observed and reported by Das and Mukhopadhyay (2014), in the sub-Himalayan region of NE India (Fig. 5d). Melanism has evolutionary significance and the selection of melanic form in the population has widely been studied in the lepidopteran moth (Cook et al. 2013). Therefore, in *H. talaca*, melanism could be natural phenomena, which would have been adopted by looper to deceive their natural enemies, as means of escaping from predators particularly in the tea garden situated near tea factories where coal is utilized during tea processing (Das and Mukhopadhyay 2014).

## Status of *H. talaca* resistance to allelochemicals and pesticides

In response to pest attacks, plants release allelochemicals that either kill the pathogens or deter them away. However, to survive against the harmful allelochemicals, pests have also weaponized themselves by developing mechanisms that reduce toxicity. Moreover, as herbivores are confronted with a large number of noxious chemicals in their plant food, they need to detoxify to make the food plant more acceptable (Schoonhoven et al. 2005) and for better utilization of the resources. Production of a higher level of detoxifying enzyme enables the insects to detoxify xenobiotics including plant secondary metabolites (Li et al. 2007). Therefore, the enzymatic activity of the looper pest in response to xenobiotics like allelochemicals and pesticides has been studied and reported widely by several authors (Das and Mukhopadhyay 2008, 2014; Das 2015; Ghosh et al. 2015). The simple diagrammatic representation of *H. talaca* responses to the alleolochemicals and pesticides has been given in Fig. 4. Tea plants contain phytochemicals such as caffeine, alkaloids, tannins, phenolics, etc. an important secondary metabolite (Mulky 1993; Yoshida et al. 1991) that exerts anti-herbivore pressures by influencing the growth and nutritional parameters. To reduce toxicity associated with these allelochemicals, herbivores react by a concomitant increase in detoxifying enzyme activity (Brattsten 1979; Mukherjee 2003). Enzymes like general esterase (GEs) and glutathione S-transferase (GSTs) has been reported as major detoxifying enzymes in the looper pest (Das and Mukhopadhyay 2008). They play a major role in reducing the toxicity associated with the allelochemicals present in the host plant (Yan et al. 1995; Scott et al. 1998; Salinas and Wong 1999; Després et al. 2007). In lepidopteran pests, the induction of GSTs and GEs by the host plants has been widely reported by many authors (Sintim et al. 2009; Yu 1982). Das and Mukhopadhyay (2014) conducted an interesting study where they analyzed the concentration of enzymes based on the flavonoid and phenolic content, which was found to be higher in young leaves compared to mature leaves (Dorkbuakaew et al. 2016). The study suggested that pests feeding on young leaves have higher levels of these enzymes compared to those feeding on mature leaves of tea plants. That is why, significantly higher levels of the above mentioned enzymes, were observed in *H. talaca* and *B.*

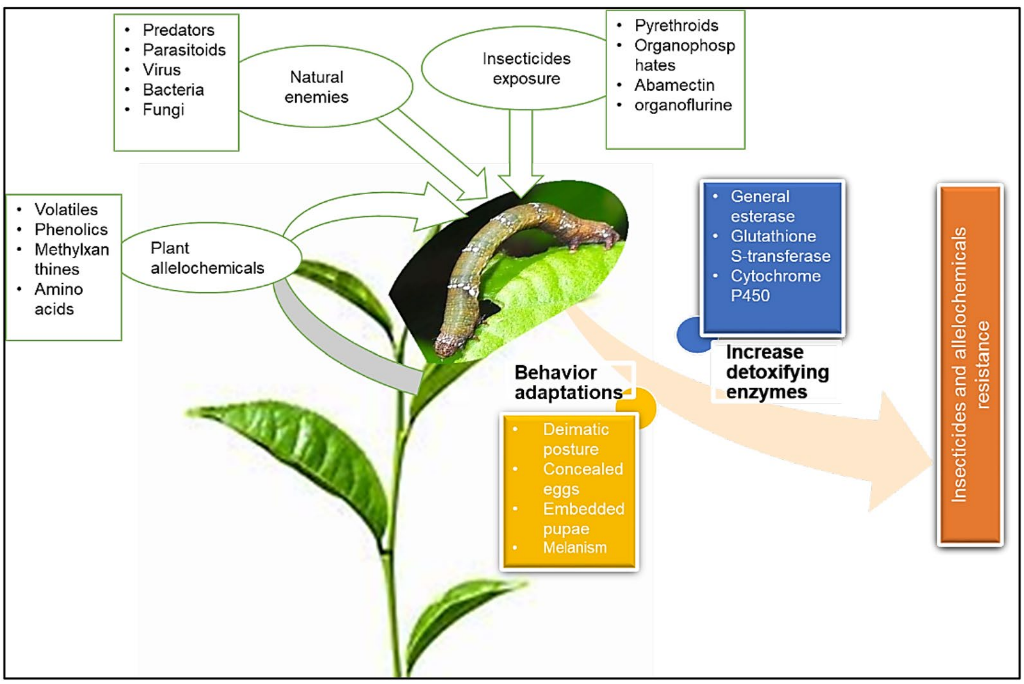


**Fig. 4** Diagramatics representation of *H. talaca* response to insecticides, plant alleochemicals and natural enemies

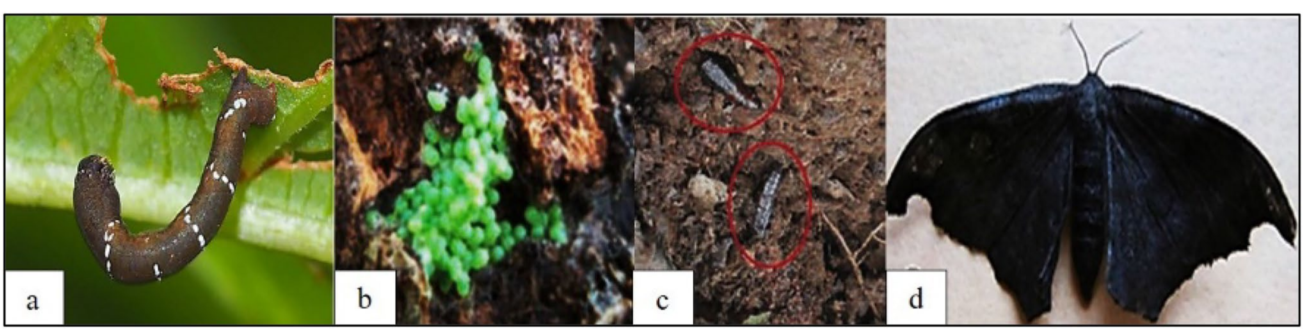


**Fig. 5** Behavioral adaptation of *H. talaca*. **a** *H. talaca* occurring "U" shaped position in response to predators. **b** eggs laid under crevices of trees, **c** Embedded pupa under soil, **d** Melanic form of female *H. talaca* (Photographs source: Roy et al. 2017)

*suppressaria,* which generally feed on young-mature leaves compared to other chewing tea pests like *A. bipunctata* and *E. aedea*, which primarily feed on mature leaves. Further, Das (2015), also supported this experiment by reporting the higher level of GEs and GSTs on pests reared on the tea plant than other host plants like *S. wallichii* and *L. speciose*. Therefore, better adaptation to tea through the production of higher quantities of detoxification enzymes led to efficient exploitation of nutrients and thereby, higher infestation cases.

Overreliance on chemical agents has resulted in the development of resistance among many target pest species, including the looper pest in tea fields. Resistance to toxins in pests can be achieved through genetic mutations and natural selection (Saha et al. 2016). Genetic mutations can provide certain individuals with inherent resistance, and when these individuals survive pesticide treatments, they pass on their resistant genes to the next generation. Natural selection favors pests with pre-existing resistance or detoxification mechanisms, allowing them to survive and reproduce, gradually increasing the overall resistance of the pest population. Additionally, pests may exhibit cross-resistance, where resistance to one pesticide confers reduced susceptibility to others with similar properties. Most of the tea-growing regions depend solely on the application of synthetic pesticides to prevent the destruction of their plants by defoliators. The repeated use of pesticides to eliminate the pests might lead to the emergence of resistance. This was determined by the fact that the looper was found to have exhibited a higher level of tolerance to the assigned pesticides, even at concentrations significantly higher than the recommended dosage and in the region where pesticides were frequently applied. It was reported that the tea-growing regions of NE India carry out 8–12 rounds of pesticide application in a year (Gurusubramanian et al. 2008). Because of this, the *H. talaca* of the NE region, especially Dooars of West Bengal have gained much tolerance to the pesticides compared to the tea-growing region of Sikkim and Kalimpong (Roy et al. 2021). Increased detoxification capacity, is another mechanism by which pests develop resistance. Research done on the resistance pattern of *H. talaca* suggested the significant role of detoxifying enzymes in imparting tolerance/resistance to the looper pest. Higher the level of these enzymes higher will be the resistance activity. Assay of the detoxifying enzymes by Das and Mukhopadhyay (2008); Ghosh et al. (2015), and Das (2015), clearly demonstrated that GSTs, GEs, and cytochrome P450 were the key enzymes imparting resistance to the pest against pesticides. Significantly, higher amounts of these enzymes were observed in *H. talaca* than in other tea pests including *B. suppressaria*. This must be because *H. talaca* has become a regular pest and remained exposed to pesticides for longer periods. According to some research, this resistance characteristic is inheritable and can pass on to the offspring. That is why; more and more challenges are coming every now and then to beat the resistance pattern of this pest.

## Future prospects

Tea industry expansion is necessary, as it is a major part of the Indian economy and a primary source of income for many families. However, before the conversion of uncultivated lands to cultivated land for tea industries, it is crucial to carefully consider the biophysical impact on the ecosystem, encompassing environmental factors, micro and macro habitats, as well as weather conditions to ensure sustainable development. Many eco-friendly, low-cost, pest-effective bio-pesticides have been assessed to be effective in controlling other tea pests. For instance, viruses like *Ectropis obliqua* NPV, *Euproctis pseudoconspera* NPV and fungi such as *Beauveria bassiana Vuill, Paecilomyces* spp*, Heptophylla picea* and *Beauveria brongniartii* have demonstrated effectiveness in controlling major tea pests in China, India, Japan and Sri Lanka (Roy and Muraleedharan 2014; Idris et al. 2020). However, such investigation into *H. talaca* has been very limited. As such, further research is required for the development of more reliable biological control agents against this pest. Moreover, studies on the behavior and life cycles of the natural enemies of this pest can help increase their population and inform strategies contributing to their effectiveness as pest control agents.

Research has found that changes in climatic conditions upsurge the growth and infestation rate of the pests in tea gardens (Agrell et al. 2005). Research focusing on the impact on tea garden ecosystems to changing climatic conditions and its subsequent effect on the prevalence of pests should be investigated. Understanding these dynamics can help in adopting pest management strategies accordingly. Researchers can also explore the effectiveness of phytosanitary measures to prevent the introduction and spread of pests in tea gardens. These practices involve quarantining, pest surveillance, and early detection systems to minimize pest outbreaks. Additionally, opting for shade trees like *Melia azedarach*, having insect-repellent properties may help in deterring pests. The current knowledge on natural pest control ecosystem services (ES) in agroecosystems is limited (Jonsson et al. 2020). To gain further insights into the pest's population dynamics and manage infestations effectively, studies on the population genetics of *H. talaca* are warranted. Therefore, by reconstructing the expansion routes of the pest and describing its demography, it would be possible to restrict further migration and the influx of additional genetic diversity. Moreover, prior to conducting field experiments, it is highly recommended to perform laboratory analyses of the pest. Prasad and Mukhopadhyay (2016) have successfully developed an artificial nutrient diet for rearing *H. talaca*, which is essential for studies in integrated pest management (IPM) programs, ensuring total management and standardization of reared insects (Parra 2012). Work also needs to be done on community involvement through workshops and awareness programs. Utilizing various communication channels for outreach can encourage the adoption of sustainable practices through effective training and technology transfer. Establishing networks, both locally and internationally may further facilitate the exchange of best practices in tea pest management.

## Conclusion

Within a short period, *Hyposidra talaca* has become a major threat to the tea industry. Further, indiscriminate use of pesticides in the tea gardens has leads to destruction of natural enemies, developed pesticides resistance and pest resurgence and causes human health hazards due to which, application of pesticides are discouraged in the tea field. Therefore, implementation of alternate controlling measures is highly recommended to prevent further destruction. Otherwise, with this rate of exploitation of the tea plants by this pest, there will be no green leaves left for harvesting. Moreover, as this pest is polyphagous, it may carry high possibility of shifting to the other crops in near future if immediate action is not taken. Hence, early detection and immediate adoption of the particular management measure for this pest is the outmost requirement. To make it possible, extensive research should be conducted focusing on its ecology, resistance pattern, host preferences and host plant interaction. Studying all the above mentioned aspects is vital for effective pest management. Furthermore, this will help in developing proactive and sustainable pest management strategies that mitigate the development and spread of resistance while ensuring the long-term effectiveness of pest management measures.

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## Declarations

**Conflict of interest** The authors declare no conflict of interest.

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