Indian Journal of Agroforestry 28(1): 20-34 (2026)

Cross-species infestation and risk of red stem borer, *Polyphagozerra coffeae* (Nietner, 1861) (Lepidoptera: Cossidae) in sandalwood agroforestry

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ABSTRACT: *Globally, the economic potential of Indian sandalwood (Santalum album L.) has attracted increasing interest from countries, government agencies, and industries, leading to significant investments in its cultivation and trade. In India, species has undergone a transition from a strictly protected forestry resource to an agroforestry crop. "However, multidimensional challenges including limited availability of quality planting material, inadequate awareness regarding cultivation practices, complex trade regulations, and the emergence of new pests and diseases continue to hinder the large-scale adoption of this species. "Polyphagozerra coffeae, once considered a minor pest, has emerged as a major threat" over the last decade has started causing severe damage in large-scale plantations, often going undetected during early stages due to lack of awareness about its biology and symptoms of infestation. This review presents a comprehensive overview of P. coffeae with emphasis on its pest status shift, biology, damage symptoms, host range, and distribution, particularly in the context of sandalwood plantations. The pest's occurrence in countries currently expanding S. album cultivation raises concerns over its cross-border threat potential. "Because sandalwood is extensively utilized for medicinal and aromatic purposes, indiscriminate use of chemical pesticides is undesirable, making Integrated Pest Management (IPM) the most suitable management approach. "Key strategies for this are early pest identification and detection, host plant monitoring, plantation hygiene, intercrop planning, Visual diagnostic features and field-level indicators are also provided to aid growers in timely and accurate identification. The insights presented aim to support sustainable sandalwood cultivation and mitigate the growing risks posed by P. coffeae in diversified agroforestry systems.*

Review Article

ARTICLE INFO

Received: 02.01.2026

Accepted: 26.03.2026

Keywords:
Indian sandalwood,
Santalum album,
Red stem borer,
Agroforestry,
Host range

1. INTRODUCTION

Indian sandalwood, *Santalum album* L. (Santalaceae), popularly referred to as the "Royal tree" of India, is one of the most treasured aromatic tree species in the world because of its unique fragrance, medicinal properties, and highly valuable heartwood oil (Paudel, 2025). Across the Indian subcontinent, irrespective of region, culture, or religion, sandalwood has historically remained an integral component of spiritual traditions, rituals, medicine, and royal heritage. The species is native to India and naturally distributed across tropical and subtropical regions between 30°N and 40°S, encompassing India, Australia, Southeast Asia, Hawaii, and several Pacific Islands (Subasinghe, 2013; Sandeep and Manohara, 2019). Sandalwood is an evergreen medium-sized tree characterized by a hemi-parasitic root system (McLellan *et al.*, 2021), which enables the plant to establish haustorial associations with a wide range of host species for absorption of water and nutrients. Historically, sandalwood played an important role not only in culture and religion but also in international trade and geopolitical relationships. Historical records indicate that sandalwood facilitated trade connections between Indian kingdoms and foreign dynasties such as the Khmer Empire of Cambodia, Champa of Vietnam, and the Song Dynasty of China (Villiers, 2001). During the British colonial period, global demand for sandalwood increased substantially (Wu, 2021), and this demand has continued into the modern era. India's annual sandalwood heartwood exports are projected to exceed 8,000 tons by 2040 (Thomson *et al.*, 2020), with sandalwood oil valued between USD 1,750–2,500 per kilogram and heartwood valued at approximately USD 100 per kilogram. Owing to its immense economic value, sandalwood paradoxically became both one of the most exploited and one of the most protected tree species in India, governed under stringent regulations related to ownership, harvest, transport, and trade. Decades of overexploitation and restrictive policies reduced annual production from nearly 4,000 tons during the 1960s to approximately 350 tons by 2014 (Aparna, 2015), which subsequently

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led to policy reforms and liberalization of sandalwood cultivation during the early 2000s. The high economic returns associated with sandalwood attracted private investors and farmers toward plantation establishment (Divakara *et al.*, 2018), resulting in expansion beyond its traditional southern Indian distribution into non-traditional states including Madhya Pradesh, Chhattisgarh, Gujarat, Rajasthan, Uttar Pradesh, Haryana, Punjab, West Bengal, and Assam (Mishra et al., 2018). During liberalization, the natural distribution of sandalwood was estimated at approximately 9,000 km², of which nearly 90% occurred in southern India (Srinivasan *et al.*, 1992; Radomiljac, 1998; Jain *et al.*, 2003). However, by 2024, sandalwood plantations had expanded to more than 23,100 hectares across India (Madhuvanthi *et al.*, 2024), emerging as one of the major agroforestry-based commercial plantation systems in the country. Simultaneously, increasing global demand and declining availability of naturally grown sandalwood accelerated the transition toward plantation-grown sandalwood (Subasinghe, 2013; Thomson *et al.*, 2020), prompting several countries including Australia, China, Fiji, Tonga, New Caledonia, Vanuatu, Malaysia, Thailand, Vietnam, and Sri Lanka to initiate commercial sandalwood plantation programmes (Subasinghe, 2013; Thomson *et al.*, 2020). Although India remains the native home of *S. album*, Australia has emerged as a global leader in commercial sandalwood plantations, with nearly 12,000 hectares established in tropical Australia (Clarke, 2006; Thomson *et al.*, 2020). Similarly, Vanuatu (Gillieson *et al.*, 2008; Page *et al.*, 2021), Loyalty Islands, and New Caledonia (Butaud, 2015) have also initiated commercial cultivation. Despite its high commercial value, sandalwood cultivation remains a long-term investment requiring nearly 15–25 years to attain harvestable maturity (Bush *et al.*, 2020; Ota *et al.*, 2022). The delayed economic returns, combined with substantial investment required for plantation establishment and theft prevention (Viswanath *et al.*, 2020; Ota *et al.*, 2022), have become major constraints limiting widespread adoption.

Furthermore, the emergence of serious pest and disease problems has intensified investor concerns by increasing the risk of plantation failure and economic losses.

The hemi-parasitic nature of sandalwood necessitates cultivation under multi-tiered agroforestry systems involving primary, secondary, and permanent host species during different stages of plant growth. More than 300 plant species have been reported as compatible hosts for sandalwood cultivation. During the early establishment phase, annual crops and herbaceous hosts such as pigeon pea (*Cajanus cajan*) (Rai, 1990), maize (*Zea mays*), groundnut (*Arachis hypogaea*), green gram (*Phaseolus radiatus*) (Thomas, 2017), touch-me-not (*Mimosa pudica*), horse gram (*Macrotyloma uniflorum*), and joyweeds (*Alternanthera* spp.) (Durai, 2021) are commonly utilized as primary hosts. These are subsequently replaced by intermediate or secondary hosts including custard apple (*Annona squamosa*), papaya (*Carica papaya*), guava (*Psidium guajava*), pomegranate (*Punica granatum*), lemon (*Citrus limon*) (Das, 2021a), drumstick (*Moringa oleifera*), and agati (*Sesbania grandiflora*) (Thomas, 2017), which support sandalwood growth during the initial 3–4 years. Eventually, permanent host trees are established within plantations, predominantly consisting of nitrogen-fixing woody species such as babul (*Acacia nilotica*) (Viswanath and Chakraborty, 2022), raspberry jam tree (*Acacia acuminata*) (Doddabasawa *et al.*, 2020; Das, 2021b), neem (*Azadirachta indica*), Australian pine (*Casuarina equisetifolia*) (Viswanath and Chakraborty, 2022), kassod tree (*Cassia siamea*) (Doddabasawa *et al.*, 2020), Indian rosewood (*Dalbergia latifolia*), shisham (*Dalbergia sissoo*), jamun (*Syzygium cumini*), Persian lilac (*Melia azedarach*), Malabar neem (*Melia dubia*) (Verma *et al.*, 2024; Arunkumar *et al.*, 2022; Radomiljac, 1998), and vilaiti babool (*Prosopis juliflora*) (Srikantaprasad *et al.*, 2022). Although such diversified agroforestry systems enhance ecological resilience and plantation productivity, they may also unintentionally create favourable environments for polyphagous insect pests. Among these, the red stem borer, *P. coffeae* Nietner (Lepidoptera: Cossidae), has recently emerged as a serious pest in sandalwood plantations, particularly in southern Indian states (Sundararaj *et al.*, 2019). The infestation potential of *P. coffeae* in sandalwood plantations has reached alarming levels, with infestation incidences of nearly 17% and mortality of approximately 10% among young plantation stock reported in affected regions (Sundararaj *et al.*, 2019). Infestation by stem borers not only weakens the tree structurally but also facilitates secondary infection by decay fungi and opportunistic pathogens, often resulting in more than one-third loss of economically valuable heartwood. Initially recognized as a pest of coffee, *P. coffeae* has demonstrated remarkable ecological adaptability through rapid expansion of its host range and is presently reported from more than 80 plant species belonging to over 35 botanical families (Table 1). Such highly polyphagous behaviour highlights its ability to persist and migrate across diversified agroforestry systems, raising serious concerns

Table. 1. Tree species infested by *Polyphagozerra coffeae* Nietner

Sl .No.	Family	Host plant	Reference
1.	Achariaceae	*Hydnocarpus kurzi* (king) Warb.	Mathur and Balwant Singh, 1960.
2.		*H. wightiana* BI.	Mathur and Balwant Singh, 1960; Beeson, 1941; Roychoudhury and Mishra, 2021.
3.		*Taraktogenus kurzii*	Beeson, 1941.
4.	Annonaceae	*Anona muricata* L..	Bhasin and Roonwal, 1954
5.		*A. sqamosa* L.	Bhasin and Roonwal, 1954: Sridhar *et al.*, 2002
6.	Casuarinaceae	*Casuarina equisetifolia* L	Nair, 2007"; Beeson, 1941; Roychoudhury and Mishra, 2021
7.	Combretaceae	*Terminalia brassii* Exell.	Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021
8.		*T. ivorensis A. Chev.*	Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021
9.		*T. bellirica* (Gaertn.) Roxb.	Beeson, 1941.
10.	Cupressaceae	*Cryptomeria* spp.	Tavares *et al.*, 2020
11.	Erythroxylaceae	*Erythroxylon coca* Lam.	Mathur and Balwant Singh, 1959.
12.	Euphorbiaceae	*Acalypha* sp.	Bhasin and Roonwal, 1954; Beeson, 1941.
13.	Fabaceae	*Acacia auriculiformis A. Cunn.* ex Benth	Nair *et al.*,1996; Wylie *et al.*, 1998
14.		*A. mangium* Willd	Nair, 2007.
15.		*Albizia falcata* (L.) Backer ex Merr	Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021
16.		*Amherstia nobilis* Wall.	Bhasin and Roonwal, 1954; Beeson, 1941.
17.		*Bauhinia malabarica* Roxb.	Beeson, 1941.
18.		*Senna auriculata* (L.) Roxb.	Beeson, 1941; Roychoudhury and Mishra, 2021.
		Syn. Cassia auriculata L	
19.		*Cassia fistula* L. (Amaltas girimalab)	Bhasin, Roonwal and Balwant Singh, 1956; Beeson, 1941; Roychoudhury and Mishra, 2021.
20.		*C. grandis* L. F.	Bhasin, Roonwal and Balwant Singh, 1956 ; Beeson, 1941; Roychoudhury and Mishra, 2021.
21.		*C. siamea* Lam.	Bhasin, Roonwal and Balwant Singh, 1956 ; Beeson, 1941; Roychoudhury and Mishra, 2021.
22.		*Leucaena leucocephala* (Lam.) de Wit	Suheri *et al.*, 2022
23.		*Pericopsis mooniana* (Thw.) Thw.	Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021
24.		*Pterocarpus dalbergioides* Roxb.	Mathur and Balwant Singh, 1960.
25.		*Robinia pseudoacacia* L.	Tavares *et al.*, 2020
26.		*Xylia dolabriformis* Benth.	Tavares *et al.*, 2020
27.		*X. xylocarpa* Taub.	Mathur and Balwant Singh, 1961; Beeson, 1941.
28.		*Castanea* spp.	Suheri *et al.*, 2022
29.	Juglandaceae	*Carya* sp.	Suheri *et al.*, 2022
30.		*Juglans regia* L.	Ahmad, 2017; Suheri *et al.*, 2022,
31.	Lamiaceae	*Clerodendrum infortunatum* L.	Mathur and Balwant Singh, 1956; Beeson, 1941; Roychoudhury and Mishra, 2021.
32.		*Vitex pubescens* Vahl	Mathur and Balwant Singh, 1961; Beeson, 1941.
33.	Lauraceae	*Cinnamomum camphora* (L.) J. Presl.	Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021.

34.		*C. zeylanicum* Breyn.	Bhasin, Roonwal and Balwant Singh, 1956 ; Beeson, 1941.
35.		*C. verum* J.Presl	Suheri *et al.*, 2022
36.		*Persea americana* Mill.	Beeson, 1941; Suheri *et al.*, 2022
		Syn. Persea gratissima C.F.Gaertn	
37.	Lythraceae	*Lagerstroemia speciosa* (L.) Pers.	Beeson, 1941.
38.	Magnoliaceae	*Manglietia conifera* Dandy	CABI, 2005.
39.	Malvaceae	*Ceiba pentandra* (L.) Gaertn.	Suheri *et al.*, 2022
40.		*Gossypium* sp.	Mathur and Balwant Singh, 1960.
41.		*Hibiscus rosa-sinensis* L.. (Shrub)	Mathur and Balwant Singh, 1960; Beeson, 1941, Roychoudhury and Mishra, 2021.
42.		*Ochroma lagopus* (Cav. ex Lam.) Urb.	Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021.
43.		*Theobroma cacao* L..	Mathur and Balwant Singh, 1961, Nair, 2007; Beeson, 1941.
44.	Meliaceae	*Chickrassia tabularis* A. Juss.	Bhasin, Roonwal and Balwant Singh, 1956; Beeson, 1941; Roychoudhury and Mishra, 2021.
45.		*Melia azedarach* L..	Mathur and Balwant Singh, 1960; Beeson, 1941.
46.		*Swietenia macrophylla* King	Petch,1926; Mathur and Balwant Singh, 1961; Beeson, 1941.
47.		*S. mahagoni* (L.) Jacq.	Mathur and Balwant Singh, 1961; Beeson, 1941.
48.		*Toona ciliata* M. Roem	Beeson, 1941; Browne, 1968; Senthilkumar and
		Syn. Cedrela febrifuga Blume and	Murugesan, 2015; Sundararaj *et al.*, 2019;
		Cedrela toona Roxb.	Roychoudhury and Mishra, 2021; Tavares *et al.*, 2020
49.		*T. sinensis* (A.Juss.) M. Roem.	Beeson, 1941; Browne, 1968; Senthilkumar and
		Syn. Cedrela sinensis Juss.	Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021.
50.	Moraceae	*Artocarpus* spp.	Suheri *et al.*, 2022
51.		*A. heterophyllus* Lam	Martinez and Ayoso, 2000
52.		*Artocarpus altilis* (Parkinson) Fosberg	CABI,2005
53.	Myrtaceae	*Eucalyptus grandis*	Tavares *et al.*, 2020
54.		*E. deglupta* Blume	Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021.
55.		*E. pellita* F.Muell.	Tavares *et al.*, 2020
56.		*Psidium guajava* L.	Beeson, 1941.
57.		*Pimenta dioica* (L.) Merr.	Abraham and Skaria, 1995
58.	Phyllanthaceae	*Phyllanthus emblica* L.	Beeson, 1941.
59.	Proteaceae	*Grevillea robusta* A. Cunn.	Mathur and Balwant Singh, 1960; Beeson, 1941; Roychoudhury and Mishra, 2021.
60.	Rosaceae	*Crataegus Tourn* ex L.	Tavares *et al.*, 2020
61.		*Eriobotrya japonica* Lindl.	Mathur and Balwant Singh, 1959; Beeson, 1941; Roychoudhury and Mishra, 2021.
62.		*Malus domestica* (Suckow) Borkh.	Tavares *et al.*, 2020
63.	Rubiaceae	*Coffea arabica* L.	Mathur and Balwant Singh, 1956.
64.		*C. robusta* Linden	Mathur and Balwant Singh, 1956; Beeson, 1941, Roychoudhury and Mishra, 2021.
65.	Rutaceae	*Citrus aurantium* L.	Bhasin, Roonwal and Balwant Singh, 1956
66.		*C. medica* L.	Bhasin, Roonwal and Balwant Singh, 1956
67.		*Citrus* spp.	Bhasin, Roonwal and Balwant Singh, 1956; Beeson, 1941; Roychoudhury and Mishra, 2021.
68.		*Clausena lansium* (Lour.) Skeels	Suheri *et al.*, 2022

69.		*Flindersia brayleana* F. Muell.	Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021.
70.	Salicaceae	*Aberia gardneri* Clos. (ketambilla)	Bhasin and Roonwal, 1954.
71.		*Dovyalis* spp.	Tavares *et al.*, 2020
72.		*Populus* spp.	Suheri *et al.*, 2022
73.	Santalaceae	*Santalum album* L.	Mathur and Balwant Singh, 1961; Beeson, 1941.
74.	Sapindaceae	*Filicium decipiens* Thw.	Mathur and Balwant Singh, 1959.
75.		*Litchi chinensis* Sonn. (Litchi)	Mathur and Balwant Singh, 1960.
76.		*Nephelium litchi* Steud.	Beeson, 1941.
77.		*Schleichera oleosa* (Lour.) Oken	Mathur and Balwant Singh, 1961.
78.		*Schleichera trijuga* Willd.	Beeson, 1941.
79.		*Dimocarpus longan* Lour.	Wen *et al.*, 2002
80.	Solanaceae	*Cestrum nocturnum* L.	Bhasin, Roonwal and Balwant Singh, 1956; Beeson, 1941; Roychoudhury and Mishra, 2021.
81.	Theaceae	*Camellia sinensis* (L.) Kuntze.	Bhasin, Roonwal and Balwant Singh, 1956; Nair, 2007.
82.		*Thea sinensis* L.	Mathur and Balwant Singh, 1961; Beeson, 1941;
83.	Verbenaceae	*Lantana indica* Roxb.	Mathur and Balwant Singh, 1960.
84.		*Tectona grandis* L.f.	Mathur and Balwant Singh, 1961; Nair, 2007; Beeson, 1941; Varma *et al.*, 2007

regarding host selection and plantation design in sandalwood cultivation. Several commonly recommended sandalwood host species including *Psidium guajava*, *Casuarina equisetifolia*, *Terminalia* spp., *Acacia* spp., and *Eucalyptus* spp. are themselves susceptible to infestation and may serve as alternate hosts and pest reservoirs facilitating migration and persistence of the insect within plantation ecosystems. Consequently, the selection of resistant or less susceptible host combinations becomes critically important for reducing infestation risks within sandalwood plantations. The capacity of *P. coffeae* to persist and migrate across multiple host species within agroforestry environments highlights the urgent need for integrated and host-aware pest management approaches that consider host susceptibility, intercrop combinations, pest migration pathways, and ecological interactions within plantation ecosystems. Although several studies have independently reported the occurrence of *P. coffeae* on different agricultural, horticultural, and forestry hosts, a comprehensive synthesis linking its expanding host range, agroforestry-mediated spread, and emerging threat to sandalwood plantations remains lacking. Furthermore, limited information is available regarding the ecological drivers responsible for the recent pest status shift of *P. coffeae* within sandalwood-based systems. Therefore, the present review critically evaluates the biology, host associations, infestation dynamics, ecological implications, and management challenges of *P. coffeae*, with special emphasis on sandalwood agroforestry systems. This review is the first comprehensive synthesis linking the expanding host range, ecological adaptability, and agroforestry-mediated spread of *P. coffeae* with the emerging risk to sandalwood-based plantation systems.

Distribution and taxonomy of *P. coffeae*

The species *P. coffeae* was originally described under the genus *Zeuzera* by John Nietner in 1861 from Ceylon (present-day Sri Lanka) and was historically known as *Zeuzera coffeae* under the genus *Zeuzera* established by Latreille in 1804. Walker (1856) subsequently elaborated the defining morphological features of the genus, which were further refined and compared in later taxonomic works by Hampson (1892), Seitz (1912), Turner (1918), and Gaede (1933). One of the earliest Indian species placed under the genus *Zeuzera* was *Z. viridicans*, described from Ganjam, Odisha, by Eschscholtz in 1821. Although the genus *Zeuzera* was once represented by nearly 52 species, only seven species are currently recognized following subsequent taxonomic revisions. Daniel (1962) included *Z. coffeae* in his systematic studies of the genus; however, the most significant modern revision was carried out by Yakovlev (2011), who established the genus *Polyphagozerra* to accommodate species previously grouped under *Zeuzera* based on distinct morphological and phylogenetic characteristics. Consequently, *Z. coffeae* was transferred to the genus *Polyphagozerra* and is now validly recognized as *Polyphagozerra coffeae*. At present, the genus includes only two recognized species, namely *P. coffeae* and *P. reticulata*.

P. coffeae is a highly polyphagous species exhibiting a broad geographical distribution throughout the tropical and subtropical regions of the Oriental biogeographical zone. The species has been reported from Bangladesh, Myanmar, Cambodia, China, India, Indonesia, Laos, Malaysia, the Philippines, Sri Lanka, Taiwan, Thailand, and northern Vietnam. Its distribution further extends into Australia, Papua New Guinea, and Pacific Island regions including Irian Jaya, indicating remarkable adaptability across diverse climatic conditions ranging from humid tropical lowlands to subtropical plantation ecosystems. The pest is particularly abundant in regions characterized by perennial plantation crops, forest plantations, and multi-storied agroforestry systems where continuous availability of woody hosts facilitates survival and population build-up. Owing to its wide host range and occurrence on economically important plantation crops, the insect is known by several common names depending on the principal crop affected. These include "carpenter moth" (Yakovlev, 2015), "coffee borer" (Beeson, 1941), "cocoa pod and stem borer," "red borer" (Arora, 1976), "red branch borer" (Kalshoven, 1940; Waller *et al.*, 2007), "red stem borer" (Sundararaj *et al.*, 2019), and "walnut borer" (Gul and Wali-ur-Rehman, 1999; Ahmad, 2017).

The extensive geographical distribution of *P. coffeae* is closely associated with its exceptionally broad host range. The insect is presently known to infest more than 80 plant species belonging to over 35 botanical families, including economically important forestry, horticultural, fruit, plantation, and shade tree species. Historically, the pest was primarily recognized as a serious stem borer of coffee (*Coffea arabica* and *C. robusta*) plantations, particularly in India and Sri Lanka (Beeson, 1941; Mathur and Balwant Singh, 1956; Roychoudhury and Mishra, 2021). However, subsequent studies revealed infestation on numerous alternate hosts including tea (*Camellia sinensis*), cacao (*Theobroma cacao*), eucalyptus (*Eucalyptus* spp.), guava (*Psidium guajava*), walnut (*Juglans regia*), teak (*Tectona grandis*), casuarina (*Casuarina equisetifolia*), and several species of *Acacia*, *Terminalia*, and *Melia*. Such extensive host diversity significantly enhances the survival, persistence, and colonization potential of the pest within plantation ecosystems by enabling continuous pest carryover between seasons and across cropping systems.

In recent years, the distributional significance of *P. coffeae* has increased considerably due to the rapid expansion of sandalwood plantations across India and other tropical countries. Several species commonly utilized as primary, secondary, and permanent hosts in sandalwood agroforestry systems are highly susceptible to infestation by *P. coffeae*. Host plants such as *Casuarina equisetifolia*, *Psidium guajava*, *Acacia* spp., *Terminalia* spp., *Melia dubia*, *Eucalyptus* spp., and *Grevillea robusta* frequently act as alternate hosts and pest reservoirs within sandalwood plantations. The coexistence of multiple susceptible hosts within a single agroforestry landscape creates favourable conditions for pest survival and migration. Such host continuity further facilitates year-round population buildup within plantation ecosystems. Consequently, the spread and establishment of *P. coffeae* are strongly associated with diversified plantation systems supporting mixed woody hosts. The occurrence of the pest across geographically distant regions and taxonomically unrelated host plants demonstrates its high ecological plasticity and invasive potential within diversified agroforestry ecosystems. This wide host adaptability has transformed *P. coffeae* from a localized plantation pest into a major emerging threat to sustainable sandalwood cultivation, particularly in southern India where sandalwood-based agroforestry systems are rapidly expanding.

Biology and Nature of Damage symptoms of *P. coffeae*

Adult moths of *P. coffeae* are white with distinct black speckles on the thorax and dark smudges on the forewings, possessing a wingspan of approximately 35–45 mm (Fig. 1a). Adult longevity ranges from 2 to 14 days, with an average lifespan of nearly seven days (Sathiamma and Bhat, 1974; Chang, 1984; Ahmad, 2017; Tavares *et al.*, 2020). Females generally commence oviposition within two days after emergence and may lay between 500 and 1,000 eggs during their lifetime. Eggs are deposited in strings or clusters within bark crevices of twigs and young stems (Stebbing, 1903; Roychoudhury and Mishra, 2021) and hatch within approximately 10 days. Oviposition within bark crevices likely provides protection against desiccation, environmental stress, and natural enemies, thereby enhancing egg survival under tropical field conditions. Newly emerged larvae produce protective silk webbing that facilitates dispersal, minimizes injury during wind movement, and prevents desiccation (Beeson, 1941). Such silk production likely represents an adaptive dispersal strategy that enhances colonization of nearby host plants within densely planted agroforestry systems. After settling on suitable hosts, larvae initiate feeding by boring into petioles, leaf bases, or branch–stem junctions (Tonini *et al.*, 1986; Monteys, 2015).

The larval stage represents the most destructive phase of *P. coffeae* and is primarily responsible for severe damage in sandalwood plantations. Larvae infest stems and branches ranging from 1.5–20 cm in diameter and enter the host through a single circular entry hole generally corresponding to the width of the larval tunnel. Once inside, larvae excavate irregular longitudinal galleries through the cambium and bast tissues, often extending up to 30 cm in length; under severe infestations, tunnelling may further extend into bark tissues and roots. Young larvae initially feed near the cambial region, enabling rapid access to nutrient-rich tissues while minimizing exposure to environmental stress and natural enemies. As development progresses, later instars penetrate deeper into the pith, sapwood, and eventually heartwood, particularly in young soft-wooded trees. This progressive shift from superficial cambial feeding to deeper internal tunnelling substantially increases physiological damage and structural weakening in sandalwood trees.

Mature larvae (Fig. 1b) attain a length of nearly 40 mm and are characterized by a brown head capsule, hardened pronotal shield, pinkish to purplish dorsal abdominal segments, yellowish ventral surface, and glossy terminal plates. Internal feeding activity disrupts vascular tissues, interferes with translocation of water and nutrients, and ultimately causes wilting, drying, and breakage of branches (Fig. 1c). A characteristic symptom of infestation is the exudation of pinkish sticky sap from entry holes, which subsequently stains the bark dark brown to black. Active infestations are further indicated by extrusion of reddish-yellow, rice grain-shaped frass pellets (Fig. 1d) through secondary ejection holes, serving as important diagnostic indicators of larval activity. As larval development advances, galleries progressively enlarge and may eventually hollow out the stem, leaving only a thin outer shell of bark and sapwood. Such extensive internal tunnelling severely compromises structural integrity and predisposes infested tissues to secondary fungal infections, thereby accelerating branch failure, decline, and mortality in economically valuable sandalwood trees. The concealed feeding behaviour of larvae also delays symptom expression, causing infestations to remain undetected until substantial internal damage has already occurred.

Young larvae generally prefer tender shoots and young branches, whereas older trees with hardened heartwood are comparatively less preferred (Stebbing, 1903). Entry into the host commonly occurs through leaf axils or bud unions. Early instars produce straight cylindrical tunnels, whereas mature larvae create broader and more irregular galleries within stem tissues. The duration of the larval stage is highly

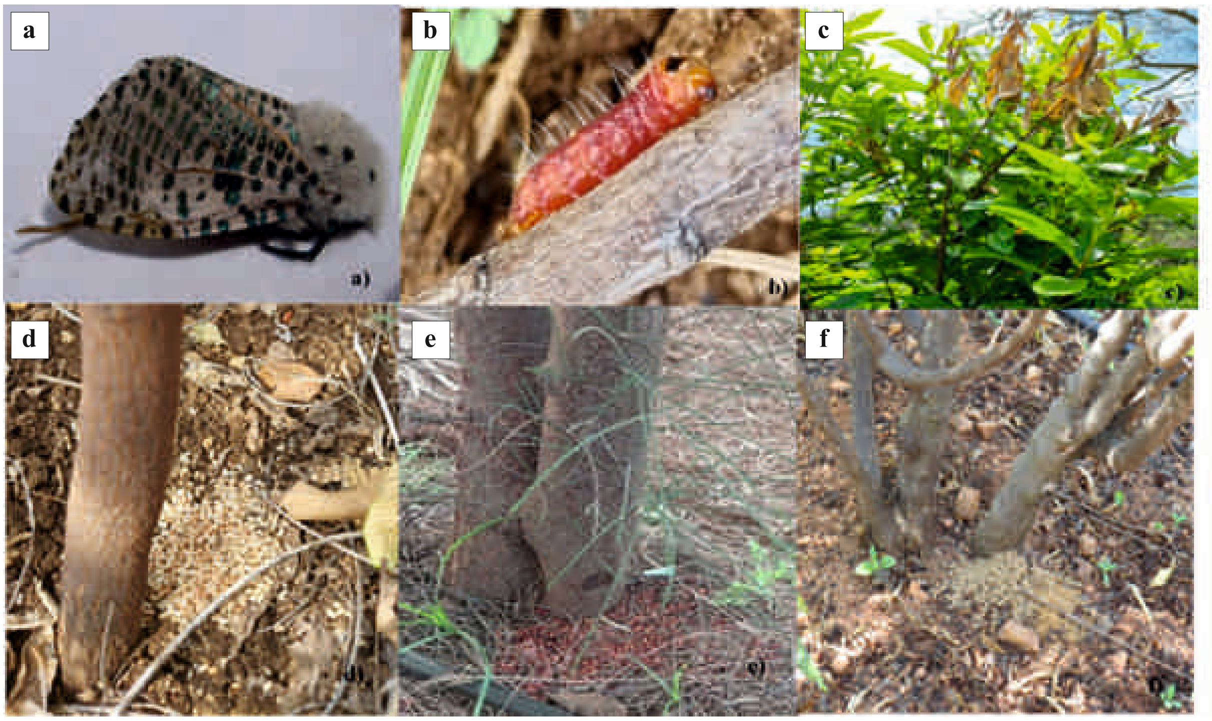

Fig 1. Life stages and infestation symptoms of *Polyphagozerra coffeae* in sandalwood-based agroforestry systems. (a) Adult moth of *Polyphagozerra coffeae*;(b) Mature larva of *P. coffeae*;(c) Wilting of sandalwood shoot tip as an early symptom of infestation;(d) Rice grain-shaped frass pellets extruded from larval galleries;(e) Frass pellets and excretion hole on *Casuarina* spp.;(f) Frass pellets and excretion hole on pomegranate (*Punica granatum*).

variable and largely influenced by host species and environmental conditions. On *Eucalyptus pellita* in Indonesia, larval development exceeds 60 days (Tavares *et al.*, 2020), whereas on *Vitis* spp. in Taiwan, the larval period ranges from 73 to 205 days (Chang, 1984). In Pakistan, larvae feeding on walnut (*Juglans regia*) complete development within approximately 150 days (Ahmad, 2017). Under southern Indian conditions, where *P. coffeae* infests sandalwood, coffee, and tea plantations, larval development generally extends for 4–5 months (Beeson, 1941). The considerable variation in larval duration across different host species indicates strong host-mediated developmental plasticity in *P. coffeae*, which likely enhances its ecological adaptability and persistence within diversified agroforestry systems. Such developmental variability may be influenced by differences in tissue moisture, nutritional quality, wood density, and defensive secondary metabolites among host plants. The prolonged larval period further increases the duration of concealed feeding within woody tissues, thereby enhancing cumulative internal damage and complicating timely detection and management in sandalwood plantations.

Prior to pupation, mature larvae prepare a circular exit hole in the infested stem or branch and seal it with a thin flap of bark. Within the tunnel, the larva constructs a loose silk mesh forming a pupal chamber reinforced with compacted frass. Pupation occurs inside this chamber, and the pupa is distinguished by backward-pointing serrations on abdominal segments and a blunt cephalic projection above the head. The pupal duration varies according to climatic conditions and host plant species. In *E. pellita* plantations in Indonesia, the pupal stage lasts 18–20 days (Tavares *et al.*, 2020), while on *Vitis* spp. in Taiwan it ranges between 19–36 days (Chang, 1984). On walnut in Pakistan, pupation lasts 17–21 days (Ahmad, 2017), whereas in India, where the pest commonly infests coffee, tea, and sandalwood plantations, the pupal period generally extends for 3–4 weeks (Beeson, 1941). However, on cacao (*Theobroma cacao*), pupation is considerably shorter, lasting only 9–13 days (Sathiamma and Bhat, 1974). At adult emergence, the pupa wriggles partially out through the exit hole, facilitating successful moth emergence. Newly emerged adults expand and dry their wings within nearly 20 minutes before flight (Beeson, 1941; Tavares *et al.*, 2020; Roychoudhury and Mishra, 2021).

The complete life cycle of *P. coffeae* generally spans 5–6 months under favourable environmental conditions. In India, Beeson (1941) reported adult emergence mainly during February, whereas pheromone trap-based studies from Indonesia demonstrated emergence beginning in March, peaking during May–June, and showing a second major flight peak during October (Suheri *et al.*, 2020; Suheri *et al.*, 2022). Similar bivoltine emergence patterns have been documented in several other regions, with major adult flights occurring during April–July and again in October (Chang, 1984; Almanoufi *et al.*, 2012; Rohani and Samih, 2012; Hegazi *et al.*, 2015). In cooler regions, larval hibernation has been observed from November to January (Ahmad, 2017), indicating adaptive diapause behaviour under unfavourable environmental conditions. The duration of the life cycle is strongly influenced by regional climatic conditions. In southern India and other low-elevation tropical regions, development is completed within 4–5 months, whereas under cooler northern Indian conditions and higher elevations, the life cycle may extend up to one year. In Myanmar, the species reportedly completes two generations annually (Beeson, 1941), while under continuously warm and humid conditions, *P. coffeae* may breed throughout the year, resulting in overlapping generations. Such climatic adaptability and continuous breeding behaviour may facilitate persistent field populations, rapid population build-up, and increased reinfestation pressure in sandalwood plantations, thereby complicating effective seasonal suppression and long-term pest management.

The concealed larval feeding behaviour of *P. coffeae* significantly complicates detection and management under field conditions. Since larvae remain protected within woody tissues for prolonged periods, visible symptoms generally appear only after extensive internal damage has occurred. This cryptic feeding habit contributes substantially to the increasing economic importance of the pest in sandalwood plantations. The deep tunnelling behaviour of mature larvae not only disrupts vascular transport but also reduces the effectiveness of contact insecticides and limits the success of conventional chemical management approaches. Consequently, sustainable management of *P. coffeae* requires integrated strategies involving early diagnosis, pheromone-based monitoring, plantation sanitation, biological control agents, and continuous field surveillance.

Host tree species for *P. coffeae*

The exceptionally broad host range of *P. coffeae* reflects remarkable ecological adaptability and largely explains its successful establishment across diverse plantation and agroforestry ecosystems. A substantial proportion of its reported hosts comprise economically important forestry, horticultural, fruit, and plantation species that are commonly cultivated alongside sandalwood, thereby facilitating continuous pest survival, inter-host movement, and year-round population persistence within plantation landscapes. Presently, *P. coffeae* has been reported from more than 80 host plant species belonging to over 35 botanical families, confirming its highly polyphagous nature and ecological plasticity.

Within the family Achariaceae, the pest has been recorded on *Hydnocarpus kurzi*, *H. wightiana*, and *Taraktogenus kurzii* (Beeson, 1941; Mathur and Balwant Singh, 1960; Roychoudhury and Mishra, 2021). In Annonaceae, infestation has been documented on *Annona muricata* and *A. squamosa* (Bhasin and Roonwal, 1954; Sridhar *et al.*, 2002). Among Casuarinaceae, *Casuarina equisetifolia* is recognized as an important host frequently associated with plantation ecosystems (Beeson, 1941; Nair, 2007; Roychoudhury and Mishra, 2021). Similarly, members of Combretaceae including *Terminalia brassii*, *T. ivorensis*, and *T. bellirica* are susceptible to infestation (Beeson, 1941; Browne, 1968; Senthilkumar and Murugesan, 2015; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021), while *Cryptomeria* spp. of Cupressaceae have also been reported as hosts (Tavares *et al.*, 2020).

Among Erythroxylaceae, *Erythroxylon coca* has been reported as a host (Mathur and Balwant Singh, 1959). In Euphorbiaceae, infestation occurs on *Acalypha* spp. and cassava (*Manihot esculenta*) (Beeson, 1941; Bhasin and Roonwal, 1954; Suheri *et al.*, 2022). Fabaceae represents one of the most important host families supporting *P. coffeae*, with infestation reported on *Acacia auriculiformis*, *A. mangium*, *Albizia falcata*, *Amherstia nobilis*, *Bauhinia malabarica*, *Cassia auriculata*, *C. fistula*, *C. grandis*, *C. siamea*, *Leucaena leucocephala*, *Pericopsis mooniana*, *Pterocarpus dalbergioides*, *Robinia pseudoacacia*, *Xylia dolabriformis*, *X. xylocarpa*, and *Castanea* spp. (Beeson, 1941; Bhasin and Roonwal, 1954; Mathur and Balwant Singh, 1960–1961; Nair *et al.*, 1996; Wylie *et al.*, 1998; Nair, 2007; Roychoudhury and Mishra, 2021; Suheri *et al.*, 2022; Tavares *et al.*, 2020). The large number of susceptible Fabaceae hosts is particularly important in sandalwood agroforestry systems because many nitrogen-fixing tree species belonging to this family are routinely utilized as permanent hosts in plantation establishment.

In Juglandaceae, hosts include *Carya* spp. and walnut (*Juglans regia*) (Ahmad, 2017; Suheri *et al.*, 2022), while members of Lamiaceae such as *Clerodendrum infortunatum* and *Vitex pubescens* are also susceptible (Beeson, 1941; Mathur and Balwant Singh, 1956, 1961). Lauraceae hosts include *Cinnamomum camphora*, *C. zeylanicum*, *Persea americana*, and *P. gratissima* (Beeson, 1941; Browne, 1968; Roychoudhury and Mishra, 2021; Suheri *et al.*, 2022). Additional hosts include *Lagerstroemia speciosa* (Lythraceae) (Beeson, 1941) and *Manglietia conifera* (Magnoliaceae) (CABI, 2005).

Within Malvaceae, several economically important hosts including *Ceiba pentandra*, *Gossypium* spp., *Hibiscus rosa-sinensis*, *Ochroma lagopus*, and cacao (*Theobroma cacao*) are attacked by *P. coffeae* (Beeson, 1941; Mathur and Balwant Singh, 1960–1961; Nair, 2007; Suheri *et al.*, 2022). In Meliaceae, infestation has been reported on *Cedrela febrifuga*, *Chickrassia tabularis*, *Melia azedarach*, *Swietenia macrophylla*, *S. mahagoni*, *Toona ciliata*, *T. sinensis*, *Cedrela sinensis*, and *Cedrela toona* (Beeson, 1941; Bhasin, Roonwal and Balwant Singh, 1956; Mathur and Balwant Singh, 1960–1961; Roychoudhury and Mishra, 2021). Members of Moraceae such as *Artocarpus* spp. are also susceptible (Suheri *et al.*, 2022), whereas within Myrtaceae, infestation has been documented on *Eucalyptus grandis*, *E. deglupta*, *E. pellita*, and guava (*Psidium guajava*) (Beeson, 1941; Tavares *et al.*, 2020; Roychoudhury and Mishra, 2021). In Phyllanthaceae, *Phyllanthus emblica* is a reported host (Beeson, 1941), while *Grevillea robusta* (Proteaceae) is also susceptible to infestation (Beeson, 1941; Mathur and Balwant Singh, 1960). Rosaceae hosts include *Crataegus* spp., *Eriobotrya japonica*, and *Malus domestica* (Mathur and Balwant Singh, 1959; Roychoudhury and Mishra, 2021; Tavares *et al.*, 2020).

The family Rubiaceae is particularly important because it includes the earliest and principal host plants from which the species derived its name, namely coffee species *Coffea arabica* and *C. robusta* (Beeson, 1941; Mathur and Balwant Singh, 1956; Roychoudhury and Mishra, 2021). In Rutaceae, hosts include *Citrus aurantium*, *C. medica*, *Citrus* spp., *Clausena lansium*, and *Flindersia brayleana* (Beeson, 1941; Bhasin, Roonwal and Balwant Singh, 1956; Suheri *et al.*, 2022). Salicaceae hosts include *Aberia gardneri*, *Dovyalis* spp., and *Populus* spp. (Bhasin and Roonwal, 1954; Suheri *et al.*, 2022; Tavares *et al.*, 2020). Importantly, within Santalaceae, the economically valuable sandalwood species *S.* is itself a confirmed host (Beeson, 1941; Mathur and Balwant Singh, 1961). In Sapindaceae, infestation has been reported on *Filicium decipiens*, *Litchi chinensis*, *Nephelium litchi*, *Schleichera oleosa*, and *S. trijuga* (Beeson, 1941; Mathur and Balwant Singh, 1959–1961). Additional hosts include *Cestrum nocturnum* (Solanaceae), tea plants *Camellia sinensis* and *Thea sinensis* (Theaceae), and *Lantana indica* and teak (*Tectona grandis*) belonging to Verbenaceae (Beeson, 1941; Bhasin, Roonwal and Balwant Singh, 1956; Mathur and Balwant Singh, 1960–1961; Nair, 2007).

The occurrence of *P. coffeae* on numerous host species commonly integrated within sandalwood agroforestry systems highlights the ecological importance of host-aware plantation planning and pest management. Intercrop combinations involving highly susceptible hosts may unintentionally facilitate pest survival, migration, and year-round persistence, thereby increasing infestation pressure on sandalwood plantations. The ability of *P. coffeae* to survive and reproduce on multiple associated host plants enables continuous population carryover and persistent reservoir formation within plantation ecosystems. Such ecological flexibility substantially increases reinfestation risk and complicates long-term management in sandalwood-based agroforestry systems.

Challenges in *P. coffeae* control of in sandalwood plantation

Effective management of *P. coffeae* remains a major challenge in sandalwood agroforestry systems. Although chemical insecticides have traditionally been employed for borer management, their effectiveness against *P. coffeae* is often inconsistent because the larvae remain concealed within woody tissues for prolonged periods. Furthermore, concerns regarding environmental contamination, non-target toxicity, and possible pesticide residue accumulation in sandalwood heartwood and essential oil considerably limit the suitability of chemical control measures in sandalwood plantations (Gahukar, 2018; Pan *et al.*, 2023). These limitations have necessitated increasing emphasis on sustainable and ecologically compatible management approaches, particularly biological control-based strategies.

Recent efforts to develop Integrated Pest Management (IPM) strategies for *P. coffeae* on different plantation and forestry hosts have shown promising results. Monitoring tools such as light traps, pheromone traps, and yellow sticky traps have been successfully utilized to detect adult emergence and seasonal flight peaks (Siregar and Tulus, 2023; Suheri *et al.*, 2022), thereby enabling timely management interventions. Monitoring assumes particular importance in the management of cryptic borers such as *P. coffeae*, where larval stages remain concealed within stems and branches, making early detection difficult (Choi and Park, 2019). Field surveillance for symptoms including wilting shoots, extrusion of gummy frass, sap exudation, and branch brittleness is therefore essential for early diagnosis and localized intervention before severe internal damage develops. Pheromone-based monitoring may further improve prediction of adult emergence periods and facilitate synchronization of management practices with vulnerable stages of the pest.

In response to the limitations of chemical management, increasing attention has been directed toward biological and botanical alternatives. Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* have demonstrated comparatively higher efficacy against *P. coffeae* than neem-based botanical formulations containing Azadirachtin (0.03–1% EC). Similar observations were reported by Suheri *et al.* (2024), who documented superior control efficacy of *B. bassiana* under both laboratory and field conditions. Likewise, Chandel *et al.* (2024) identified *Heterorhabditis bacteriophora* as an effective biological control agent against related stem-boring pests in apple orchards, indicating the broader potential of entomopathogenic organisms for management of concealed internal borers. Although neem-based insecticides remain widely preferred because of their broad-spectrum activity and comparatively low mammalian toxicity (Schmutterer and Singh, 2002; Abd El-Salam *et al.*, 2018), their reduced efficacy against *P. coffeae* may largely result from inadequate penetration into deeply tunneled woody tissues where larvae remain protected. The comparatively superior performance of entomopathogens suggests that biological agents capable of infecting concealed larval stages may offer greater long-term potential for sustainable management of the pest.

Despite encouraging progress, a standardized IPM strategy specifically tailored for *P. coffeae* management in sandalwood plantations is still lacking. The high economic value and sensitive end-use of sandalwood products further restrict management options and necessitate the development of residue-safe and environmentally sustainable control measures. Current evidence suggests that an integrated strategy combining regular monitoring, plantation sanitation, biological control agents, selective botanical applications, and timely destruction of infested plant material may provide the most effective and sustainable approach for long-term suppression of *P. coffeae* in sandalwood agroforestry systems.

Discussion

Managed sandalwood plantations have emerged as a major commercial investment sector in India, encouraging both farming communities and private entrepreneurs to cultivate *S. album* under agroforestry, farm forestry, and mixed plantation systems." (Bunney *et al.*, 2023; Chavan *et al.*, 2024). Although sandalwood cultivation offers considerable economic opportunities because of the high market demand for heartwood and essential oil, the transition of sandalwood from natural forest ecosystems into intensive plantation systems has also introduced complex ecological and phytosanitary challenges (Ota *et al.*, 2022; Viswanath *et al.*, 2020). Presently, large-scale sandalwood plantations covering approximately 23,100 hectares are being actively established across India by farmers and private stakeholders (Madhuvanthi *et al.*, 2024). "However, many new growers and commercial investors remain inadequately informed about the ecological challenges and emerging pest and disease threats associated with sandalwood cultivation in agroforestry systems." (Sundararaj *et al.*, 2019; Das, 2021a). "Although more than 150 insect species have been reported feeding on S. album, most historically remained minor pests and rarely attained serious economic importance." (Remadevi *et al.*, 2005). However, during recent years, stem borer complexes have increasingly emerged as major limiting factors affecting plantation productivity and survival. Sundararaj *et al.* (2019) documented the occurrence of stem and bark borers such as *Indarbela quadrinotata* Walker and *Aristobia octofasciculata* Aurivillius in sandalwood plantations along with the red stem borer *P. coffeae*. At the time of those observations, *P. coffeae* was regarded as a comparatively minor pest; however, over the past six years, it has evolved into one of the most serious threats to sandalwood plantation establishments, with infestation levels reaching 11–22% in certain plantation regions (Shanbhag *et al.*, 2026). This transition from a minor pest to a major economic pest represents a significant ecological concern for the expanding sandalwood industry.

The emerging pest status of *P. coffeae* is likely driven by multiple interacting ecological and anthropogenic factors. The rapid expansion of large-scale sandalwood plantations into non-traditional cultivation regions has increased the density, continuity, and spatial connectivity of susceptible host plants, thereby facilitating pest establishment, survival, and dispersal. Unlike naturally distributed sandalwood populations occurring within heterogeneous forest ecosystems, plantation-based agroforestry systems frequently consist of repeated combinations of susceptible host species planted in close proximity, creating highly favourable conditions for pest colonization and persistence. The highly polyphagous nature of *P. coffeae*, with its ability to infest more than 80 host plant species across 35 botanical families, further enhances its ecological adaptability within diversified agroforestry systems. Several species commonly integrated as primary, secondary, or permanent hosts in sandalwood plantations—including guava (*Psidium guajava*), casuarina (*Casuarina equisetifolia*), eucalyptus (*Eucalyptus* spp.), acacia (*Acacia* spp.), pomegranate (*Punica granatum*), and teak (*Tectona grandis*)—are themselves susceptible to infestation by *P. coffeae* (Beeson, 1941; Nair, 2007; Sundararaj *et al.*, 2019; Roychoudhury and Mishra, 2021; Suheri *et al.*, 2022). These associated host plants may therefore function as persistent pest reservoirs, facilitating continuous population carryover and inter-host migration within plantation landscapes. The extensive host range of *P. coffeae* reflects considerable ecological plasticity and suggests adaptive evolutionary mechanisms enabling successful colonization of taxonomically diverse woody hosts.

The hemi-parasitic nature of sandalwood cultivation further contributes to the ecological complexity of pest management. Successful establishment of sandalwood requires the integration of primary, secondary, and permanent host plants at different growth stages (Radomiljac, 1998; Thomas, 2017; Doddabasawa *et al.*, 2020; Verma *et al.*, 2024). While agroforestry diversification generally improves biodiversity and ecological resilience (Amare *et al.*, 2019), the presence of multiple susceptible host plants within the same system may unintentionally favour highly polyphagous pests such as *P. coffeae*. The simultaneous occurrence of suitable annual crops, horticultural species, and perennial woody hosts provides a continuous ecological network that supports pest survival throughout the year. Such agroforestry complexity may explain the increasing incidence of *P. coffeae* in managed plantations compared with naturally dispersed sandalwood populations.

The concealed feeding behaviour of *P. coffeae* significantly increases its destructive potential and complicates management efforts. Larvae remain hidden within stems and branches for prolonged periods, feeding internally on cambial tissues, sapwood, and eventually heartwood, before visible symptoms become apparent (Beeson, 1941; Chang, 1984; Ahmad, 2017; Tavares *et al.*, 2020). Consequently, infestations are often recognized only after wilting, stem breakage, drying of branches, or complete mortality of young plants occurs. The cryptic internal feeding habit significantly limits the efficacy of conventional pesticide applications and necessitates monitoring-based integrated pest management approaches.

Internal tunnelling also predisposes affected stems to secondary invasion by decay fungi and opportunistic pathogens, further accelerating deterioration of economically valuable heartwood. Since sandalwood is primarily cultivated for its medicinal and aromatic heartwood, stem damage caused by *P. coffeae* may result in severe economic losses extending beyond simple plant mortality.

Climate variability may further intensify the future threat posed by *P. coffeae* in sandalwood agroforestry systems. Several studies on stem borers and plantation pests have demonstrated that increasing temperatures and altered rainfall patterns can influence insect developmental rates, voltinism, survival, and geographical distribution (Hegazi *et al.*, 2014; Suheri *et al.*, 2022). Warmer environmental conditions may accelerate larval development and increase the number of generations per year, thereby facilitating faster population buildup. Additionally, drought stress and environmental fluctuations may physiologically weaken sandalwood plants, increasing their susceptibility to infestation. Considering that sandalwood plantations are increasingly being established in semi-arid and climatically variable regions of India, understanding the interaction between climate stress and pest incidence has become increasingly important.

The global expansion of sandalwood cultivation also raises important concerns regarding the future distribution and economic significance of *P. coffeae*. Countries such as Australia, Indonesia, Vietnam, Thailand, Cambodia, Fiji, Vanuatu, and Malaysia are increasingly promoting commercial sandalwood cultivation (Subasinghe, 2013; Thomson *et al.*, 2020; Bush *et al.*, 2020; Page *et al.*, 2021). Interestingly, many of these countries have already reported the occurrence of *P. coffeae* or related stem borers on forestry and horticultural hosts (Varma *et al.*, 2007; Ahmad, 2017; Tavares *et al.*, 2020; Suheri *et al.*, 2022). This overlap between expanding sandalwood cultivation zones and the known geographical distribution of *P. coffeae* suggests a high likelihood of future pest outbreaks in emerging sandalwood industries outside India. Therefore, proactive monitoring and host-aware plantation planning will be essential to minimize future transboundary pest risks.

Management of *P. coffeae* in sandalwood plantations remains particularly challenging because of the medicinal and commercial importance of sandalwood products. Extensive application of synthetic chemical insecticides is generally undesirable, as pesticide residues in sandalwood heartwood and oil may compromise product quality and medicinal acceptability (Gahukar, 2018; Pan *et al.*, 2023). Consequently, pest management in sandalwood plantations should primarily rely on integrated pest management (IPM) approaches emphasizing biological control, regular monitoring, plantation sanitation, and careful host selection. Monitoring tools such as pheromone traps, light traps, and sticky traps have shown promise in detecting adult emergence and monitoring population dynamics in plantation systems (Suheri *et al.*, 2020; Suheri *et al.*, 2022; Siregar and Tulus, 2023). Early diagnosis based on visual symptoms such as wilting shoots, gummy exudation, frass extrusion, and drying branches is also essential for timely intervention.

Recent studies suggest that biological control agents may offer safer and more sustainable management alternatives against *P. coffeae*. Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* have demonstrated promising efficacy against stem borers under laboratory and field conditions (Suheri *et al.*, 2024). Similarly, entomopathogenic nematodes such as *Heterorhabditis bacteriophora* have shown effectiveness against related internal borers in orchard systems (Chandel *et al.*, 2024). However, because larvae remain protected within woody tissues, many botanical and contact insecticides exhibit limited effectiveness against the pest. Therefore, future management research should focus on improving delivery systems for biological agents, developing pheromone-based mass trapping technologies, and formulating eco-compatible IPM protocols specifically tailored for sandalwood agroforestry systems.

Intercrop and host plant selection also play a critical role in the successful management of *P. coffeae*. In plantation regions where the pest is already prevalent, inclusion of highly susceptible host species may substantially increase infestation pressure and management costs. In the present observations, host plants such as guava, casuarina (Fig.1e), and pomegranate (Fig.1f), were found to support *P. coffeae* infestation and potentially contribute to pest persistence within sandalwood plantations. Therefore, in addition to selecting high-quality sandalwood planting material, identification and selection of comparatively resistant host combinations is equally important for long-term plantation sustainability. Since sandalwood was introduced into intensive agroforestry systems only during the last two decades, scientific understanding regarding optimal host combinations, pest ecology, and host-mediated infestation dynamics remains limited. Consequently, every emerging pest issue associated with sandalwood plantations requires immediate scientific attention and region-specific investigation.

Overall, the emergence of *P. coffeae* as a serious pest in sandalwood agroforestry systems represents an important ecological and economic challenge for the rapidly expanding sandalwood industry. Its broad host range, concealed feeding habit, adaptability to multi-host agroforestry environments, and increasing geographical spread collectively complicate management efforts. Sustainable mitigation of this pest will require integrated approaches involving early diagnosis, ecological understanding, region-specific host selection, biological management strategies, and continuous monitoring. Future research should prioritize evaluation of resistant host combinations, pest-host chemical ecology, climate-driven distribution shifts, and development of standardized IPM protocols suitable for medicinally important tree crops such as sandalwood.

Conclusion

The emergence of *P. coffeae* as a serious pest in sandalwood agroforestry systems represents an important ecological and economic concern for the expanding sandalwood industry. Its broad host range, concealed feeding habit, and adaptability to multi-host agroforestry environments make management particularly difficult. The increasing use of susceptible intercrops and permanent hosts in sandalwood plantations may unintentionally facilitate pest persistence and spread. Sustainable management therefore requires integrated approaches involving early diagnosis, host-aware plantation design, biological control, and continuous monitoring. Considering the rapid global expansion of sandalwood cultivation, proactive research and region-specific integrated pest management strategies are essential to minimize future economic losses.

Funding Support:

CAMPA provided financial support to carry out particular research - Sanction Order No.75/2019/ ICFRE (R)/RP/SFRESPE (CAMPA)/ AICRP-3/Main File/28 dated:10/01/2020

Conflict of Interest: Author declares there is no conflict of interest

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