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STINGLESS BEES AS CROP POLLINATORS IN INDIA: FROM FLORAL VISITATION TO POLLINATION POTENTIAL AND AGRICULTURAL APPLICATION

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ABSTRACT
Stingless bees (Meliponini) are significant pollinators with a great potential for use in Indian agriculture, yet their importance to crop pollination is not majorly explored. This review focusses on the current knowledge on the diversity, distributions, foraging behaviour and pollination potential of stingless bees, with major emphasis on their suitability as pollination units in Indian agriculture. We investigated the evidence for crop visitation, transfer of pollen, contribution to plant reproductive success in terms of fruit/seed set and overall agricultural benefits, while considering the notable traits that impact the pollination effectiveness of stingless bees, including colony characteristics, foraging behaviour, floral constancy, bee-flower and environmental compatibility. Furthermore, the possibility of managing stingless bee colonies has been discussed in relevance to hive establishment and multiplication techniques, food resources, hive placement methods, protection from pesticide and natural enemies as well as hive contribution in protected cultivation practices. Finally, major research gaps are recognized, including identification of diverse bee species and colony availability, adoption of standardized pollination experiments, the process of pairing specific bee species with targeted crops and most significantly economic valuation and farmer adoption. By bridging these gaps, it is possible to support the development of sustainable and locally adapted stingless bee pollination systems in Indian agriculture.

KEYWORDS: Stingless bees, diversity and distributions, pollination effectiveness, managed pollination units, crop-bee matching, economic valuation, Indian agriculture.

1. INTRODUCTION

Pollination is the process of transfer of pollen grains from the male part (anther) to the female part (stigma) of the flower (Faegri & Pijl, 1979). The pollen carriers are generally classified into two types: biotic (animal vectors) and abiotic (non-living vectors) (Faegri & Pijl, 1979). The most common abiotic mechanisms are anemophily (pollination by wind) accounting for nearly 98% of abiotically pollinated plants (Faegri & Pijl, 1979) , while some aquatic plants, such as *Vallisneria* spp., utilize water to transfer their pollen (hydrophily) (Wylie, 1917). However, most of the flowering plants (87-90%) are animal-pollinated (IPBES, 2016). Beyond their ecological role, animal pollination is essential for sustainable food supply, directly influencing the yield and/or quality of 75% of globally significant crops (Klein et al., 2007; Potts et al., 2010). It is estimated that 5-8% of worldwide crop production could be in jeopardy without animal pollination services (Aizen & Harder, 2007). Although a wide range of animals including insects, mammals, birds, rodents, bats and lizards can act as pollinators (Abrol, 2012), insects are the most significant and diverse group of biotic pollinators (Faegri & Pijl, 1979). Insect pollinators include bees, flies, wasps, butterflies, moths, ants and thrips (IPBES, 2016).

Bees are the largest pollinator group, with more than 20,000 described species, and they visit nearly 90% of global food crops (IPBES, 2016). Among bees, the European honey bee species, *Apis mellifera* is the most widely adopted commercial pollinator, with more than 81 million hives deployed across agricultural land to meet crop pollination demands (IPBES, 2016). However, European honey bees are not regarded as efficient pollinators for all crops. Furthermore, overdependence and multiple introductions into uninhabited areas has raised several concerns such as increased competition for food resources and nesting sites with native pollinators (Prendergast et al., 2021), acting as pathogen vectors, (Guzman-Novoa et al., 2015; Stout & Morales, 2009) and suppression of reproduction in native plants and conversely, increased spread of exotic weeds in introduced regions (Simpson et al., 2005). In parallel, substantial honey bee colony losses have been observed over the years (FAOSTAT, 2018), posing a serious threat to pollination services rendered. Therefore, encouraging wild pollinators by protecting native habitats in agricultural landscapes may help to provide more stable crop pollination services and support biodiversity restoration (IPBES, 2016). This review highlights stingless bees as promising alternative to honey bees for crop pollination. In addition to supporting crop pollination, stingless bees can diversify farming household income through hive byproducts such as honey, bee pollen and propolis.

2. Beyond honey bees: Exploring stingless bees for crop pollination

Stingless bees (Meliponini) are promising alternatives for commercial crop pollination (Heard, 1999; Roubik, 1995). They are a highly diverse and abundant group of eusocial bees with over 550 described species, distributed across many tropical and subtropical regions across the globe (Eardley, 2004) including Southeast Asia, Australia, Africa and tropical America (Michener, 2007). Because colonies forage broadly while individual bees often exhibit floral constancy, stingless bees are theoretically well suited for crop pollination (Slaa et al., 2006). They have been recorded visiting nearly 90 crop species (Heard, 1999) and provide valuable pollination services. For example, Ramalho (2004) observed that stingless bees accounted for about 70% of total foraging by bees, even though they represented only 7% of local bee diversity in Brazil rainforests. Similarly, in Malaysia, stingless bees pollinate nearly 25% of angiosperms compared with 11% reported for *Apis* bees (Sakai et al., 1999). Stingless bees have also been domesticated for centuries, especially by the people in Latin America (Crane, 1983, Weaver and Weaver, 1981). Earlier reports suggest that stingless bees have been successfully transported from naturally occurring tropical and subtropical areas to much colder climates using temperature-controlled hives or rooms like the research undertaken in Japan and at Utrecht University in the Netherlands (Amano, 2004; Amano et al., 2000; Maeta et al., 1992). Many stingless bee species can be managed in artificial hives for commercial pollination (Nogueira-Neto, 1997) and several traits make them suitable for this purpose. The suitable traits for domestication are listed below,

a) Unlike *Bombus*, stingless bee colonies do not die after reproduction and are naturally long-lived, making individual hives easier to maintain over extended periods (Murillo, 1984).

b) They do not possess a functional sting, which makes them suitable for crop pollination in enclosed systems such as greenhouses and cages. (Slaa et al., 2006).

c) Many stingless bee species forage effectively in enclosed structures and under suitable climatic conditions and because their hives are perennial, they can forage year-round (Slaa et al., 2006). Furthermore, their shorter foraging range compared with honey bees, may also improve foraging efficiency in green houses (Kakutani et al., 1993; Seelay, 1985). For example, in Brazil, a stingless bee species, *Melipona fasciculata* has been used to enhance pollination services in eggplant grown under greenhouses (Nunes-Silva et al., 2013). Their visitation has been evidently shown to improve fruit set in crops like lychee, avocado and macadamia (Heard, 1994), greenhouse capsicum (Greco et al., 2011) and mango (Singh et al., 2024). In India, stingless bees are recognized as important pollinators of crops such as ash gourd (Chauhan et al., 2019), sunflower (Kumar et al., 2020), coriander (B.S.; Vignesh et al., 2024b), and field-grown and greenhouse cucumber (Chauhan & Singh, 2022; Tej et al., 2017), etc.

d) Stingless bees are reported to be less affected by pests, diseases and parasites than domesticated honey bees (Nogueira-Neto, 1997). Overall, their ease of domestication, adequate worker populations, non-aggressive nature (Heard, 1999; Roubik, 1995), lower susceptibility to diseases and suitability for managed hives indicate that stingless bees can provide valuable pollination services across a wide range of economically important crops.

3. Stingless bees: Diversity and distributions

Stingless bees belong to the subfamily Meliponinae within the family Apidae, superfamily Apoidea, order Hymenoptera, and class Insecta. Like honey bees, they are colonial eusocial insects (Michener, 2007). However, they differ from honey bees in several morphological traits, including reduced wing venation and a vestigial sting (Wille, 1983), as well as distinctive nesting behaviour, such as using cerumen - a mixture of resin and wax as a building material (Roubik, 2006). They depend on pollen and floral nectar for survival (Grüter, 2020) like honey bees and are also closely related to bumble bees, carpenter bees, and orchid bees (Roubik, 1989). Within Meliponinae, the tribes Meliponini and Trigonini are represented by the genera *Melipona* and *Trigona*, respectively (Francoy et al., 2009; Wille, 1983). Stingless bees in Asia and Africa mostly belong to the tribe Trigonini, which includes genera such as *Trigona*, *Nanotrigona*, *Tetragona*, and *Plebeia*. Among these, *Trigona* is the most diverse genus, comprising more than 130 species. Most *Trigona* species are relatively small and long-winged, whereas *Melipona* species are generally larger and short-winged, with some approaching the size of honey bees (Crane, 1992). The Neotropical region is the centre of stingless bee diversity (Wille, 1979), containing approximately 77% of all described species, compared with 16% in the Indo-Malayan/Australasian region and 7% in the Afrotropical region (Grüter, 2020). India harbors at least 25 stingless bee species (Table 1), mostly in the genera *Tetragonula* (16 species), *Lepidotrigona* (5 species), and *Lisotrigona* (4 species) (Table 1) (Rasmussen, 2013; Viraktamath & Jose, 2017; Viraktamath & Roy, 2022; Viraktamath et al., 2023; Viraktamath & Thangjam, 2021; Viraktamath & Thangjam, 2022). In genus *Tetragonula*, ‘*iridipennis*’ is the most widespread species, especially in eastern and southern India (Rahman et al., 2015). In genus *Lepidotrigona*, ‘*arcifera*’ is the most widespread species, first reported from

Table 1. Diversity of stingless bees in India

S.No.	Name of species	Distributions	References
1	*Lepidotrigona amruthae* (Viraktamath & Thangjam, 2022)	Mizoram	(Viraktamath & Thangjam, 2022)
2	*Lepidotrigona arcifera* (Cockerell, 1929)	Andhra Pradesh, Karnataka, Assam, Kerala, Nagaland, Meghalaya, Tamil Nadu, Sikkim, West Bengal	(Narendra et al., 2021; Rahman et al., 2015; Rasmussen, 2013; Vijayakumar, 2014)
3	*Lepidotrigona rajithae* (Viraktamath & Thangjam, 2022)	Mizoram	(Viraktamath & Thangjam, 2022)
4	*Lepidotrigona sikkimensis* (Viraktamath & Thangjam, 2022)	Sikkim	(Viraktamath & Thangjam, 2022)
5	*Lepidotrigona thenzawlensis* (Viraktamath & Thangjam, 2022)	Mizoram	(Viraktamath & Thangjam, 2022)
6	*Lisotrigona caccaiae* (Nurse, 1907)	Madhya Pradesh, Sri Lanka	(Nurse, 1907; Rasmussen, 2013)
7	*Lisotrigona chandrai* (Viraktamath & Jose, 2017)	Kerala	(Viraktamath & Jose, 2017)
8	*Lisotrigona mohandasi* (Jobiraj & Narendran, 2004)	Kerala	(Jobiraj & Narendran, 2004; Rasmussen, 2013)
9	*Lisotrigona revanai* (Viraktamath & Sanjan Jose, 2017)	Maharashtra	(Viraktamath & Jose, 2017)
10	*Tetragonula ashishi* (Viraktamath & Jagruti, 2022)	Maharashtra	(Viraktamath & Roy, 2022)
11	*Tetragonula bengalensis* (Cameron, 1897)	Assam, Arunachal Pradesh, Meghalaya, Nagaland, West Bengal	(Das et al., 2024; Kunal et al., 2020; Rahman et al., 2015; Rasmussen, 2013)
12	*Tetragonula calophyllae* (Shanas & Faseeh, 2019)	Goa, Kerala	(Krishna & Alex, 2024; Shanas & Faseeh, 2019)
13	*Tetragonula gressitti* (Sakagami, 1978)	Arunachal Pradesh, Nagaland	(Chauhan & Singh, 2020; Rathor et al., 2013)
14	*Tetragonula iridipennis* (Smith, 1954)	Andhra Pradesh, Karnataka, Chhattisgarh, Kerala, Himachal Pradesh, Tamil Nadu, Punjab, West Bengal, Uttarakhand	(Charan et al., 2023; Chauhan, 2024; Choudhary et al., 2021; Gouda et al., 2024; Pavithra et al., 2013; Rahman et al., 2015; Raju, 2009; Rasmussen, 2013; Sabatina et al., 2023; Tej et al., 2017)
15	*Tetragonula kyrdemkulaiensis* (Viraktamath & Rojeet, 2021)	Meghalaya	(Viraktamath & Thangjam, 2021)
16	*Tetragonula laeviceps* (Smith, 1857)	Gujarat	(Gadhiya & Pastagia, 2019; Khambhu et al., 2022)
17	*Tetragonula perlucipinnae* (Shanas & Faseeh, 2019).	Kerala	(Shanas & Faseeh, 2019)
18	*Tetragonula praeterita* (Walker, 1860)	Sri Lanka	(Hadimani et al., 2024; Rahman et al., 2015; Rasmussen, 2013; Shanas & Faseeh, 2019)
19	*Tetragonula ruficornis* (Smith, 1870)	Delhi, Haryana, Punjab, Uttarakhand, Uttar Pradesh	(Viraktamath & Roy, 2022)

20	*Tetragonula shishirae* (Viraktamath, 2022)	Rajasthan	(Viraktamath & Roy, 2022)
21	*Tetragonula shubhami* (Viraktamath, 2022)	Chhattisgarh	(Viraktamath & Thangjam, 2021)
22	*Tetragonula srikantanathi* (Viraktamath, 2022)	Tripura	(Viraktamath & Roy, 2022)
23	*Tetragonula sumae* (Viraktamath, 2022)	Tamil Nadu	(Abraham & Shanas, 2021; Shanas & Faseeh, 2019)
24	*Tetragonula travancorica* (Shanas & Faseeh, 2019)	Karnataka, Kerala, Tamil Nadu	(Ramakrishna et al., 2024)
25	*Tetragonula vikrami* (Viraktamath, 2022)	Karnataka	(Viraktamath & Roy, 2022)

Testa bridge of the Himalayas in India (Cockerell, 1929). Unlike *Tetragonula* bees, *Listotrigona* bees are less common which has been recorded in some parts of southern India and Madhya Pradesh and also the wing venetion is significantly decreased (Michener, 2000).The diversity of stingless bees is still undiscovered in several places across the Indian subcontinent. Hence, future diversity studies can potentially increase the number of stingless bee species recorded so far.

4. Biological and behavioural traits determining pollination potential in stingless bees

4.1 Colony characteristics

Many characteristics of stingless bee colonies influence their ability as pollinators in crop plants, which include:
a) perennial colonies comprising a queen and numerous workers, which facilitate pollination activity over extended periods without having to re-establish every season as in annual colonies formed by *Bombus* spp. (Roubik, 2023),
b) large and persistent worker populations, significant for foraging on mass flowering crops where flowers become available in abundance for relatively short time periods, for example, *Tetragonula pagdeni* colonies contained approximately 800-1200 adult workers and a single colony was able to pollinate a substantial number of tomato plants under greenhouse conditions (Wongsa et al., 2023),
c) ‘forager recruitment’ meaning workers recruit nestmates to rewarding floral resources resulting in increased exploitation of that resource (Nieh & Roubik, 1995; Roubik, 2023) which is more efficient compared to a process where each individual insect has to find the source,
d) large food reserves stored in nests - this allows colonies to survive when resource availability is low. This process encourages foragers to collect floral rewards beyond needs and result in intensive floral visitation rates (Roubik et al., 1986),
e) domestication - many stingless bee species can be maintained in hives, inspected, fed, propagated and transported (Nogueira-Neto, 1997),
f) manageability of hives - the absence of functional sting makes the colony handling much easier and safer than handling honey bees, potentially increasing their importance in greenhouse cultivation (Kakutani et al., 1993); colonies rarely abscond since the old queens are flightless (Inoue et al., 1984) and they are often resistant to parasites and diseases of honey bees (Delfinado-Baker et al., 1989).

4.2 Foraging behaviour

Pollination efficiency ultimately depends on how individual workers forage on flowers. Stingless bees have been reported to make repeated visits when floral resources are abundant (Singh et al., 2024). Successful foragers communicate the location of profitable resources to nestmates, leading to collective exploitation of flowering patches. This recruitment behaviour is one of the key biological traits influencing their potential as crop pollinators (Heard, 1999). Foraging activity varies throughout the day and is shaped by environmental cues, such as temperature, humidity, and solar radiation, as well as floral cues, including resource availability, anthesis, and nectar and pollen availability. Therefore, effective pollinators must be active when viable pollen and receptive stigmas are present. For example, *T. pagdeni* showed peak foraging activity in the morning, coinciding with tomato flowering under greenhouse conditions (Wongsa et al., 2023). Similarly, *T. iridipennis* showed peak visitation during maximum stigma receptivity in mango (Singh et al., 2024). A 2022 report also found that the foraging behaviour of *T. iridipennis* was strongly influenced by flower traits, time of day, floral anthesis, floral richness, and bee species (Layek et al., 2022). This species also showed resource-gathering strategies similar to honey bees, with many mixed foragers collecting both nectar and pollen, indicating traits favorable for crop pollination (Layek et al., 2022).

4.3 Floral constancy and crop fidelity

Floral constancy refers to the repeated visitation of the same plant species by a bee during a single foraging trip or over a longer period. This behaviour can improve pollination efficiency because it increases the likelihood that pollen is transferred between flowers of the same species. Crop fidelity, the tendency of foragers to continue exploiting a crop until its floral resources are depleted, is especially important in agricultural landscapes where crop plants are often mixed with wild vegetation. In *Trigona carbonaria*, 88% of pollen-load samples collected from individual foragers during single trips contained ≥97% of one pollen type. The same study reported that 88% of bees visited the same plant on the first day, followed by 82% on the second day and 73% on the third day (White et al., 2001). These findings suggest that floral constancy in *T. carbonaria* may increase conspecific pollen transfer and thereby enhance pollination efficiency (White et al., 2001). Another study reported that 97% of pollen foragers from nine different stingless bees collected in Brazil visited only one pollen source per foraging trip (Ramalho et al., 1994). Although floral constancy has been reported in some stingless bee species, it is not an inherent characteristic of all stingless bee species.

4.4 Bee-flower compatibility

Bee-flower compatibility is a notable determinant of bee pollination effectiveness because successful pollination depends on the interaction between bee morphology, floral structure and foraging behaviour. Even though stingless bees are smaller than honey bees, their size enables them to collect rewards from small as well as morphologically complex flowers. Body size, proboscis length, and flower handling behaviour determine which flowers are effectively pollinated by stingless bees. Abundant bee populations and high visitation rates do not indicate high pollination potential; actual physical contact with floral reproductive structures and successful transfer of pollen onto receptive stigmas play a significant role (Heard, 1999; Layek et al., 2022).

4.5 Environmental adaptability

The high environmental adaptability of stingless bees makes them effective pollinators across diverse tropical and subtropical regions. As perennial, colony-forming bees, they can exploit warm conditions in both native and agricultural landscapes. However, this adaptability should not be interpreted as unlimited tolerance to environmental disturbance. For example, forest and native vegetation cover can support stingless bee populations, whereas agricultural intensification and urbanization may reduce their abundance and species richness. Their value as crop pollinators therefore depends not only on their tolerance of environmental stress but also on the continuous availability of sufficient alternative floral resources in the surrounding landscape (Amano et al., 2000; Heard, 1999).

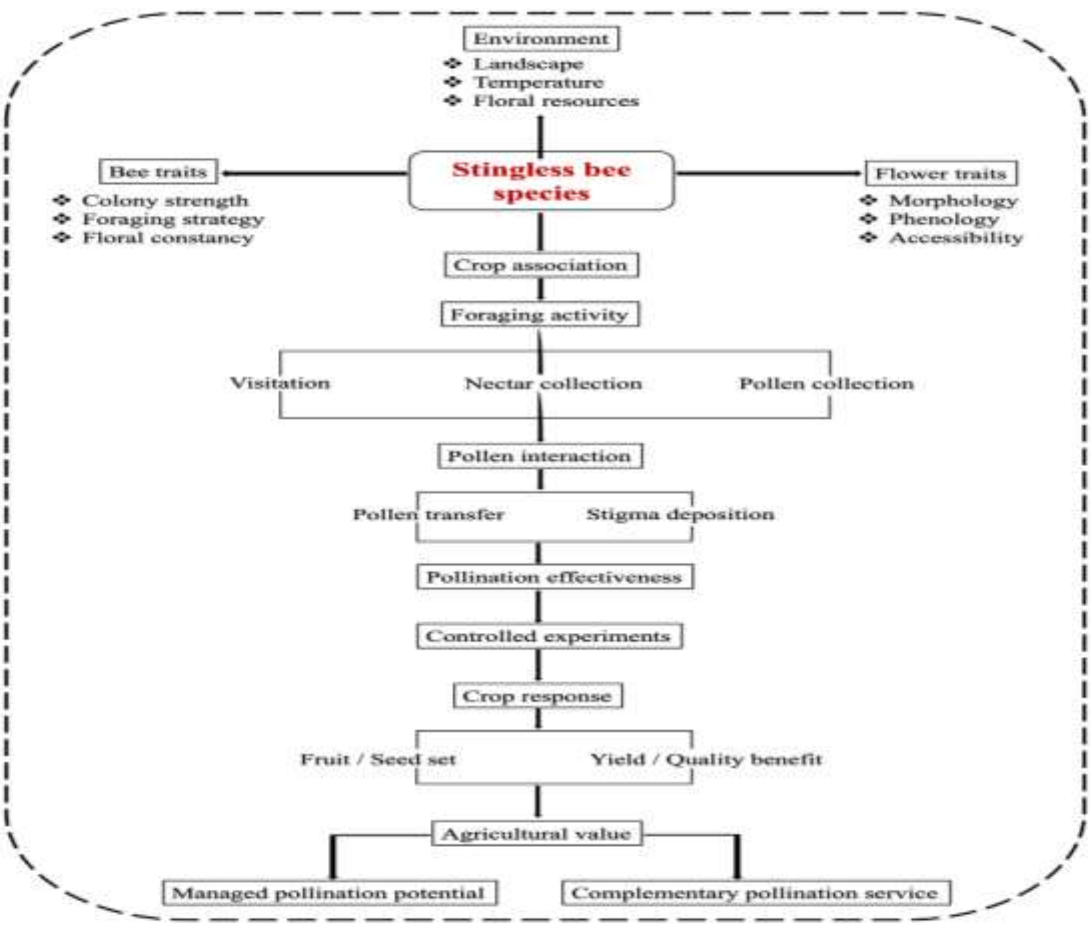

Figure 1. Conceptual framework for assessing the pollination potential of stingless bees in agricultural crops

5. Stingless bees: Floral visitation to Crop yield

5.1 Do stingless bees visit flowers?

Floral visitation provides the first evidence of interaction between crop species and bees. In the tropics, >1,000 plant species are cultivated for food, fibre, beverages, medicine, and spices (Purseglove, 1968, 1972; Rehm & Espig, 1991; Roubik, 1995). Of these, stingless bees have been recorded visiting nearly 90 tropical crop species, indicating broad potential for stingless bee–crop interactions. They are considered important floral visitors in crops such as tomato, melon (Bhambure, 1958; Mohana Rao & Suryanarayana, 1988), macadamia (Heard, 1994; Masís & Lezama, 1991), cucumber (Bhambure, 1958), mango (Singh, 2020), onion (Rao & Suryanarayana, 1989), strawberry (Kakutani et al., 1993), coconut (Engel & Dingemans-Bakels, 1980; Hedström, 1986) and mango (Cortopassi-Laurino et al., 1991; Freitas & Paxton, 1996; Iwama & Melhem, 1979; Singh, 1989; Singh et al., 2024) (Table 2). For example, *Tetragonula mellipes* accounted for 62.7% of total visits recorded on mangoes in Northern Territory, Australia (Singh, 2020) and *T. pagdeni* was recorded as the dominant floral visitor in mango under greenhouse conditions (Wongsa et al., 2023). However, these records indicate only the possibility of crop–bee interactions; visitation alone does not confirm crop pollination. This is because visitation patterns cannot show whether the visitor contacts the flower's reproductive structures or transfers compatible pollen.

Table 2. Reported interactions of stingless bee species with agricultural crops across the world

S.No.	Stingless bee species	Crops	Activity reported	References
1	*Trigona* spp.	*Capsicum annum* (Capsicum)	Pollen collection	(Heide, 1923)
		Hevea brasiliensis (Rubber)	Pollen collection	(Jayarathnam, 1970)
		Luffa cylindrica (Sponge gourd)	Visitation	(Pande & Verma, 2021)
		Macadamia integrifolia (Macadamia)	Pollen collection	(Heard, 1987; Heard & Exley, 1994)
		Mangifera indica (Mango)	Visitation, pollen deposition and fruit yield/quality benefit	(Singh, 2020; Sosa-Nájera et al., 1994)
		Nephelium lappacaum (Rambutan)	Visitation	(Uji, 1987)
2	*Trigona iridipennis*	*Allium cepa* (Onion)	Pollen and nectar collection	(Rao & Suryanarayana, 1989; Sihag, 1985)
		Benincasa hispida (Ash gourd)	Fruit yield benefit	(Chauhan et al., 2019)
		Capsicum annum	Visitation, pollen and nectar collection, fruit set response and fruit yield/quality benefit	(Chauhan & Imtinaro, 2024; Rakshitha et al., 2023, 2026; B.S. Vignesh et al., 2024)
		Citrullus lanatus (Water melon)	Fruit quality benefit	(Chauhan & Singh, 2021)
		Coriander sativum (Coriander)	Visitation, pollen and nectar collection and fruit yield benefit	(Shelar & Suryanarayana, 1981; B.S.; Vignesh et al., 2024a)
		Cucumis anguria (Gherkin)	Visitation	(Rakshitha et al., 2023)
		Cucumis melo (Muskmelon)	Visitation	(Rakshitha et al., 2023)
		Cucumis sativus (Cucumber)	visitation	(Rakshitha et al., 2023)

		Elettaria cardamomum (Cardamom)	Pollen collection	(Chandran et al., 1980)
		Foeniculum vulgare (Fennel)	Fruit yield benefit	(Layek et al., 2002)
		Helianthus annus (Sunflower)	Visitation	(Goel & Kumar, 1981; Painkra & Kumaranag, 2019)
		Luffa cylindrica	Visitation and fruit yield and quality benefits	(Chauhan, 2026)
		Momordica charantia (Bitter gourd)	Visitation	(Rakshitha et al., 2023)
		Sechium edule (Squash)	Visitation and fruit set response	(Manoharan et al., 2025)
		Solanum lycopersicum (Tomato)	Visitation	(Rakshitha et al., 2023)
		Zea mays (Maize)	Visitation and pollen collection	(Layek et al., 2025)
3	*Trigona carbonaria*	*Litchi chinensis* (Lychee)	Pollen and nectar collection	(King et al., 1988)
4	*Trigona laeviceps*	*Capsicum annum*	Fruit set response and fruit yield/quality benefit	(Rakshitha et al., 2026)
5	*Trigona nigra*	*Persea americana* (Avocado)	Pollen and nectar collection	(Ish-Am et al., 1999)
6	*Trigona spinipes*	*Psidium guajava* (Guava)	Pollen collection	(Cortopassi-Laurino & Ramalho, 1988)
		Helianthus annus	Visitation	(Moreti & Marchini, 1992)
7	*Trigona nigerrima*	*Coffea arabica* (Coffee)	Visitation	(Roubik, 1998)
		Persea americana	Pollen and nectar collection	(Ish-Am et al., 1999)
8	*Trigona fulviventris*	*Coffea arabica*	Visitation	(Roubik, 1998)
		Persea americana	Pollen and nectar collection	(Ish-Am et al., 1999)
9	*Trigona corvina*	*Sechium edule* (Squash)	Fruit set response	(Wille et al., 1983)
10	*Trigona angustula*	*Coffea arabica*	Visitation	(Roubik, 1998)
		Capsicum annum	Visitation	(Free, 1993)
		Mangifera indica	Pollen collection	(Anderson et al., 1982)
11	*Trigona thoracica*	*Averrhoa carambola* (Star fruit)	Pollen deposition	(Engel & Dingemans-Bakels, 1980)
12	*Trigona hyalinata*	*Helianthus annus*	Visitation	(Moreti & Marchini, 1992)
13	*Tetragonula biroi*	*Momordica charantia* (Bitter gourd)	Fruit set response and fruit quality benefit	(Indraswari Suhri et al., 2022)

14	*Tetragonula minangkabau*	*Fragaria ananassa* (Strawberry)	Pollen deposition and fruit quality benefit	(Nogueira-Neto et al., 1959; Roubik, 1998)
15	*Nanotrigona testaceicornis*	*Fragaria ananassa*	Visitation	(Sosa-Nájera et al., 1994)
16	*Nanotrigona perilampoides*	*Persea americana*	Pollen and nectar collection	(Ish-Am et al., 1999)
17	*Geotrigona* spp.	*Helianthus annus*	Visitation	(Goel & Kumar, 1981)
		Persea americana	Pollen and nectar collection	(Ish-Am et al., 1999)
18	*Scaptotrigona postica*	*Myrciaria dubia* (Camu-camu)	Visitation	(Peters & Vasquez, 1986)
19	*Scaptotrigona pectoralia*	*Persea americana*	Pollen and nectar collection	(Ish-Am et al., 1999)
20	*Scaptotrigona mexicana*	*Persea americana*	Pollen and nectar collection	(Ish-Am et al., 1999)
21	*Hypotrigona pothieri*	*Bixa Orellana* (Achiote)	Pollen collection	(Lobreau-Callen et al., 1990)
		Psidium guajava Guava)	Pollen collection	(Lobreau-Callen et al., 1990)
22	*Melipona* spp.	*Cocos nucifera* (Coconut)	Pollen transfer	(Engel & Dingemans-Bakels, 1980; Hedström, 1986; Sommeijer et al., 1983)
		Coffea arabica	Visitation	(Nogueira-Neto et al., 1959)
		Myrciaria dubia	Visitation	(Peters & Vasquez, 1986)
23	*Melipona favosa*	*Averrhoa carambola*	Pollen deposition	(Engel & Dingemans-Bakels, 1980)
24	*Melipona marginata*	*Psidium guajava*	Pollen collection	(Kleinert-Giovannini & Imperatriz-Fonseca, 1987)
25	*Melipona quadrifaciata*	*Psidium guajava*	Pollen collection	(Guibu et al., 1988)
26	*Melipona melanoventer*	*Bixa Orellana*	Pollen collection	(Maues & Venturieri, 1995)
27	*Melipona fuliginosa*	*Bixa Orellana*	Pollen collection	(Wille, 1976)
28	*Melipona seminigra*	*Bixa Orellana*	Pollen collection	(Absy et al., 1984)
29	*Melipona rufiventris*	*Bixa Orellana*	Pollen collection	(Absy et al., 1984)
30	*Partamona bilineata*	*Persea americana*	Pollen and nectar collection	(Ish-Am et al., 1999)
31	*Paratamona cupira*	*Sechium edule*	Fruit set response	(Wille et al., 1983)
32	*Plebia frontalis*	*Persea americana*	Pollen and nectar collection	(Ish-Am et al., 1999)
33	*Friesella schrottkyi*	*Helianthus annus*	Visitation	(Cortopassi-Laurino et al., 1991)

5.2 Stingless bees: Pollen transfer and subsequent fruit/seed set

The second level of evidence should demonstrate that stingless bees contact floral reproductive structures and directly contribute to pollen transfer. Bees may spend considerable time on flowers without touching the anthers or stigmas, so visitation does not necessarily result in pollen transfer. For example, *T. pagdeni* was observed crawling over tomato stamens while foraging (Wongsa et al., 2023), whereas *T. iridipennis* carried the highest pollen loads and deposited more mango pollen grains per visit than other recorded mango visitors (Singh, 2020). These studies provide evidence of actual pollen transfer by stingless bees.

Controlled experiments that measure reproductive outcomes, such as fruit/seed set and fruit quality, provide much stronger evidence of stingless bee pollination. For example, in greenhouse tomatoes, *Nanotrigona perilampoides* increased fruit set to 83±4.2%, compared with 78.5±6.4% under mechanical vibration and 52.6±7.6% in no-pollination treatments (Cauich et al., 2004). The same study also recorded the highest seed counts in stingless bee–pollinated tomatoes. Under similar tomato greenhouse conditions, *T. pagdeni* produced 85±4.2 fruits per 100 flowers, compared with 79.5 per 100 flowers under mechanical vibration and only 15 per 100 flowers in control blocks without pollinators (Wongsa et al., 2023). Other examples include a 78.9% increase in strawberry fruit set with *Tetragonula laeviceps*, and higher melon fruit production by *Heterotrigona itama* (6.1 fruits per plant) compared with open pollination (2.6 fruits/plant) and no pollination (0.2 fruits/plant) (Atmowidi et al., 2022). Fruit set alone does not fully reflect a pollinator's contribution to crop reproductive success; fruit quality is also important. For example, under greenhouse conditions, *Melipona quadrifasciata* produced tomatoes with 15% greater fresh mass and 41.1% more seeds than fruits obtained through open pollination (Silva-Neto et al., 2019). Together, these findings indicate that stingless bees can make measurable contributions to crop pollination.

6. Can Indian stingless bees be managed as pollinating agents?

Stingless bee colonies are perennial, can be maintained and propagated in man-made hives, making them a suitable candidate for continued use as pollination units for extended periods. Although colony establishment and management are possible, specific standardized protocols for Indian stingless bees needs elaborate study. In southern India, practical hive deployment studies have been undertaken in stingless bee, *T. iridipennis* - a colony strength of nearly 2000 bees were maintained in artificial hives in greenhouse cucumber inside a 500m^2 area in Tamil Nadu and maintained throughout the flowering period (Kishan et al., 2017). A similar study was undertaken in greenhouse cucumber cultivation in Assam (Sen et al., 2023). Hive deployment of stingless bees in open field conditions in India still require systematic approach towards hive design, optimal colony strength, colony multiplication, placement density, and seasonal management. Population of stingless bee tends to increase in areas where crop plants are close to forest patches; for example, Rambutan orchards near forests in Thailand had significantly higher stingless bee visitation and yields (Sritongchuay et al., 2016). In northern Australia, stingless bees were found to be 145 times more efficient than *Apis mellifera* in mango orchards adjacent to native vegetation (Singh et al., 2024). Similarly, a study carried out in West Bengal, India observed the occurrence of seasonal death of *T. iridipennis* due to food scarcity (Layek & Karmakar, 2025). These findings demonstrated the need to maintain alternative floral resources in the surroundings in addition to crop of interest to sustain optimal colony strength. Furthermore, exposure to pesticides and natural enemies should also be thoroughly studies before deploying stingless bee colonies for pollination. On the contrary, use of stingless bees in protected cultivation has given promising results in India. *T. iridipennis* has been reported to increase yield by over 9% compared to control in cucumber greenhouse cultivation in Tamil Nadu (Kishan et al., 2017). Use of *T. iridipennis* colonies increased yield by fivefold compared to pollinator excluded plants in a study in Assam (Sen et al., 2023). These studies show that stingless bees have the potential to serve as good pollinating agents in protected cultivation practices.

7. Future scope

In future, the first priority should be given to forming standardized species- and crop-specific pollination system. First, species identification, distribution mapping and colony availability should be thoroughly discussed. Second, standardized pollination experiments need to be undertaken on visitation, anther/stigma contact, pollen transfer, contribution to fruit set and yield as supposed to focusing mainly on visit frequency alone. Third, specific bee-crop matches need to be identified to know which Indian stingless bee species prove to be efficient and effective for meeting specific crop pollination needs. Finally, economic aspects such as colony production and deployment costs, pollination induced yield gains, profitability, adaptability, and additional income from maintained hives in the form of hive byproducts should be assessed to completely understand the benefits of Meliponiculture in India.

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