Weed flora in field margins: An essential off-season resource for the insect pollinators in Moringa (*Moringa oleifera* Lam.)

Pakkirisamy Manikandan[1], Subramanian Malarvannan[1], Rajaraman Ranjith[1], Bryony K. Willcox[2], Raj Rengalakshmi[1*], Deepa Senapathi[2]

[1]*M. S. Swaminathan Research Foundation, Tamil Nadu, India*

[2]*University of Reading, Berkshire, UK*

*Corresponding author: rengalakshmi@mssrf.res.in

Abstract

The weed species in agricultural fields offer tangible benefits, in spite of its detrimental impact on crop growth and productivity. Several weed species support beneficial natural enemies and pollinators which are crucial for eco-friendly agriculture. This study was conducted to understand the importance of weed species in the conservation of insect pollinators in Moringa (*Moringa oleifera* Lam.) crop fields in the Dindigul district of Tamil Nadu, India. Before the flowering phase, observations were recorded during January–March 2021 from ten sites with five to eight-year-old perennial Moringa trees. A total of 20 species of flower visitors or insects were observed on 49 weed species; of these, 15 insects have been reported as Moringa pollinators in earlier studies. The weed species belonging to the Asteraceae, Malvaceae and Amaranthaceae families were more attractive to pollinators from the Apidae, Lycaenidae, Nymphalidae, Syrphidae and Hesperidae families. The study showed that 39 weed species were in the flowering phase during the non-flowering window of Moringa thereby serving as an important alternative resource for insect pollinators of Moringa during this lean period. The study also observed that three weed species attracted more diverse and a greater number of pollinators than others. This paper provides a detailed account of the weed species and their attractiveness to the flower visitors and their diversity and frequency of appearance. A deeper understanding of weed species–pollinator interactions will support the designing of effective field management measures to sustain and augment pollinators in the context of increasingly changing habitats.

Keywords: Insect pollinators, Weed species, Floral resources, Off-season, Conservation, Moringa

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Introduction

Around 75% of global food crops are partially or wholly dependent on animals for pollination (Losey and Vaughan 2006; Klein et al. 2007). However, insect pollinators and the pollination service they provide are declining across agricultural landscapes due to crop intensification, monocropping, landscape simplification and transformation, and changes in natural habitats (Ricketts 2004; Isaacs et al. 2009; Naug 2009; Potts et al. 2010; Goulson et al. 2015; Otto et al. 2016; Sánchez-Bayo and Wyckhuys 2019; Balfour and Ratnieks 2022a). While insect pollinators benefit from crops in terms of obtaining floral resources, other factors in the landscape, such as floral diversity (e.g. other crop and non-crop plants, including weeds) and nesting sites (e.g. field margins, bunds, semi-natural habitat), are also important for meeting their pollen, nectar and habitat requirements (Landis et al. 2005; Requier et al. 2015).

Within an agricultural context, weeds compete with economically valuable crops for critical resources such as water and nutrients and are controlled to prevent this. Yet, they can play an important role in supporting insect crop pollinators (Norris and Kogan 2005; Requier et al. 2015; Morrison et al. 2021; Blaire M. Kleiman, Koptur, and Jayachandran 2021; Balfour and Ratnieks 2022b). For example, weeds present in field margins and field bunds provide additional floral resources for insect pollinators, and this enhances pollination services and productivity of nearby crops (Biesmeijer et al. 2006; Hannon and Sisk 2009; Bretagnolle and Gaba 2015; Garratt et al. 2017; Ollerton 2017).

It has been reported that the weed diversity in the field margins and the nearby areas has led to an increase in crop productivity of seed crops and cross-pollinated fruits and vegetables (Morandin et al. 2007; Nicholls and Altieri 2013) due to the abundance of floral and nesting resources (Ricketts et al. 2008; Shackelford et al. 2013). The wide floral diversity in the agriculture ecosystem and nearby areas positively influences the pollinator diversity and activities in the fields (Biesmeijer et al. 2006; Persson and Smith 2013; Bretagnolle and Gaba 2015). Furthermore, despite providing fewer floral resources (pollen and nectar) compared with crops, the availability of weeds in the 'off-flowering season' and presence in less disturbed areas such as field bunds and intercropped regions are important factors for sustaining floral resources throughout the year (Landis et al. 2005; Klein et al. 2007; Bretagnolle and Gaba 2015; Requier et al. 2015). A well-managed weed population rather than a clean and weed-free field increases the wild pollinator diversity, and timely management of weeds to maintain the lower extent in field bunds helps in increasing diversity of pollinators and crop yields (Christmann et al. 2017). The standard agronomic weed management practices are production intensive and productivity oriented. They fail to recognize and integrate the supplementary services of weed species from an ecological service provision perspective. This leads to loss of natural and semi-natural field edges or margins, field bunds with hedges and tree species, and undisturbed patches within and nearby fields during the cropping and non-cropping seasons. The negative impacts of such agronomic practices are a cause for concern (Manalil et al. 2011), with structural changes in composition, decrease in the abundance of many species, dominance of a small number of species and even extinction of few (Meyer et al. 2013). Such changes during the non-flowering phase of the cultivated crops are crucial and disrupt season-long nectar/pollen and nesting site availability to sustain pollinators (Ricketts et al. 2008; Shackelford et al. 2013). The destruction of such natural or semi-natural habitats has led to reduction in foraging and nesting sites, which is one of the chief factors for the decline in the number of wild pollinators (Hendrickx et al. 2007; Winfree et al. 2009).

The studies proving co-benefits of fostering field margins with flowering weed species on crop productivity help to standardize the agronomic practices for managing weed hedge rows and policies that promote pollinators. There are attempts to develop a trade-off between ecological and economic (farming) interests by promoting floral species in the field margins as hedges in the agricultural and horticultural ecosystems. Several models have been in practice with similar underlying principles. The prominent ones are ecological intensification in farmland landscapes (Dore et al. 2011; Bommarco, Kleijn, and Potts 2013), ecological engineering (Westphal et al. 2015; Ganser, Knop, and Albrecht 2019) and farming with alternative pollinators (Christmann et al. 2021). A deeper understanding of the weed–pollination interaction and biology will be helpful in developing locally suited strategies (Bretagnolle and Gaba 2015). In addition, specific weed-management strategies need advanced research on augmenting pollinators without reduction in crop productivity and change in pollinator behaviour to ensure nesting habitats and sources of pollen and nectar throughout the year (Nicholls and Altieri 2013; Rollin et al. 2013).

Against this backdrop, this present study focuses on *Moringa oleifera* Lam. (henceforth referred to as Moringa), which is an economically important crop that requires less water for cultivation. In the recent past, especially in view of the climatic changes, it has been increasingly cultivated by smallholders for its green pods in drought-prone areas as an adaptation strategy. It is a highly cross-pollinated crop and predominantly depends on insects for pollination. The flowers are creamy white in colour, fragrant, hermaphroditic, pentamerous, zygomorphic and loosely arranged in a panicle that grows to a length of 15–20 cm. The flower anthesis takes place between 6.00 a.m. and 12.00 noon, followed by pollen anthesis and nectar secretion. The average number of pollen grains recorded were 23,525 per flower (Bhattacharya and Mandal 2004). On average, Moringa flowers are available for 45–60 days during February–May and 55–70 days during September–November. Bhattacharya and Mandal (2004) reported that the percentage of fruit set under netting conditions was 1% whereas it was 10.28% under natural conditions and 0% under bagging conditions. The most common insect flower visitors belong to four orders, namely Thysanoptera, Hymenoptera, Lepidoptera and Coleoptera. Of these, *Xylocopa* sp. (Hymenoptera) is an effective pollinator. It is evident that the pollinators are crucial for pod production in Moringa, and hence, deeper knowledge of maintenance of pollinators during the non-flowering season is fundamental from a sustainable production perspective. Although there have been studies focused on improving productivity from an agronomic perspective, the importance of pollinators vis-à-vis productivity is still understudied. The present study is the starting point in filling the key knowledge gap on how to maintain floral resources for pollinators and the role of weeds in that respect. The study is vital to smallholders in semi-arid region whose livelihoods are dependent on Moringa cultivation.

The goal of this study is to investigate two main research questions: How many flowering weed species that potentially support pollinators during the non-flowering period of Moringa are commonly available in its field margins? What are the native insect pollinators of Moringa utilizing the available weed flora during the non-flowering period? The answers to these questions and knowledge about pollinators are vital for farmers to make informed and practical decisions on weed management.

Material and methods

Study site: The study was conducted in ten perennial Moringa fields (variety: *Karumbu*; plate 1., landholding size: 0.4–2.5 ha; field margins: length 40 m, average width 0.5–1.0 m) in Reddiarchatram block (10°21'56.0916''N and 77°58'14.3652''E, 287 m a.s.l.) of Dindigul district, Tamil Nadu, India (Fig. 1), during 2021, in the non-flowering season, that is, January–March. The region has a semi-arid climate with an average annual rainfall of

930.50 mm and maximum and minimum temperatures of 31.50ºC and 20.8ºC, respectively. The major crops cultivated in the plains of Reddiarchatram block are Moringa, maize, coconut, citrus fruits, onion, gooseberry and beetroot. Of these, Moringa occupies almost 30% of the total cropped area. In the study site, there has been a silent shift in the cropping pattern from a wide diversity to very few selected crops such as maize, cotton, flower crops, Moringa and so on because of water scarcity and the changing rainfall pattern. Preference is high among small landholders for perennial Moringa since it has low water requirement (drip irrigation is commonly followed) and high value and is less expensive to maintain and cultivate.

Sampling weeds and insect visits: The weed flora on the field margins were sampled using a random 1 m^2 (1 m x 1 m) quadrat method. Different weed species with flowers in 1 m^2 of wooden frame were recorded. Sampling was done on consecutive days in ten locations in 20 m^2 area of each location. Three samples per month with an interval of 10 days were observed on available weeds to record the species richness. Weed species were identified using the *Hand Book on Weed Identification*(Naidu 2012).

Flower visitors and their behaviour: The insect pollinators were surveyed and recorded through sweep net sampling and visual observation of flower visitors on weed species. Observations were conducted along 20-m transects within the Moringa field margins. Flower visitor surveys were done in 10-day intervals from January to March 2021. For each month, three samples were taken at each location for a total of 30 samples per month. Flower visitor surveys were conducted in dry weather with a temperature range between 20ºC and 30ºC and wind speed <5 beaufort. Different insect species visiting and staying on the weed flowers in the selected locations were closely observed for their frequency of visit and relative abundance. A total of 5 h (8.00–11.00 a.m. and 3.00–5.00 p.m.) of active sampling was done on each sampling day at each site. The sampling effort in terms of time spent was constant for each location.

Sweeps were made randomly on the flowering plants to collect all the insects visiting or hovering near the flowers of any flowering weed plant in the selected locations. The collected insects were transferred to a killing jar containing ethyl acetate. The specimens were brought to the laboratory and pinned, labelled and dried for further identification. All specimens have been deposited in the field laboratory of the M. S. Swaminathan Research Foundation, Kannivadi, Dindigul, Tamil Nadu, India.

Study of pollinators on selected weeds: Based on the number of insect pollinator visits and insect species attractiveness, the three most common weed species (*Abutilon indicum*, *Cleome gynandra* and *Leucas aspera* – Plate 2,3 and 4) were selected for in-depth study. The total number of insect pollinators from different species visiting the selected weed species was recorded. Ten observations were made on each weed species at weekly intervals. Each observation was done for 2 hours h (from 9.30 a.m. to 11.30 a.m.), and a total of 100 h were spent in observation.

Data analysis: The floral resources were divided into three categories based on the number of insect species attracted as per the method suggested by Zameeroddin and Belavadi (2020): highly attractive, if > 10 species; attractive, if 6–10 species; and less attractive, if 1–5 species. To study the species diversity and abundance of flower visitors, the Simpson diversity index (D) and Shannon diversity index (H) were calculated as follows:

$D = \sum (n_i * (n_i - 1))/N * (N - 1))$, and

$H = -\sum [(pi) * In(pi)]$,

where pi is the proportion of individuals of *i*-th species in a whole community, that is, pi = *n*/*N*, where *n* is the number of individuals in the species and *N* is the total number of individuals in the community.

To visualize the interactions of insect pollinators and weed species, we built bipartite networks with the three main weed species. Each network was weighted using visitation data recorded across the ten Moringa fields (overall network) or from individual fields (field-level networks). The bipartite package in R was used to create the network figures (Dormann et al. 2008).

Results

The current study recorded a total of 3,366 flower visits and 49 weed species across the ten Moringa fields (Table 1). Of the recorded weed species, the majority belonged to the family Asteraceae (9), followed by Malvaceae (8), Amaranthaceae (6), Euphorbiaceae and Capparidaceae (4 each), Fabaceae, Lamiaceae and Tiliaceae (3 each), Asclepiadaceae (2) and Polygonaceae, Papaveraceae, Acanthaceae, Nyctaginaceae, Brassicaceae, Sapindaceae and Rubiaceae (1 each) (Table 1; Fig. 2). The floral phenology of 34 weed species out of the 49 recorded in the Moringa fields coincided with the non-flowering phase of Moringa in the study sites (Table 2). However, sparse flowering was recorded even in the remaining 15 weed species. The growth habits of the observed weed species were predominantly herbs (42), followed by shrubs (5) and climbers (2). Of the 42 herbs, 18 species were annual and 24 biennial/perennial, and the 7 shrubs and climbers were perennial in nature (Table 1). Of the total recorded species, 4 were invasive and 11 were under priority invasive species while the remaining 34 were from tropical/Asian/Indian regions (TNPIPER 2021).

Flower visitors of common weeds: Twenty species of flower visitors were recorded on weeds in the Moringa fields (Table 2). Of these, 11 were from the order Hymenoptera, which included 5 each from the families Apidae and Halictidae and 1 from Vespidae. Moreover, 5 species were from the order Lepidoptera, which included 4 from the family Lycaenidae and 1 from Hesperidae. The remaining 4 species were from the order Diptera, which included 2 species from the family Syrphidae and 1 each from Muscidae and Dolichopodidae (Fig. 3). Of the 20 flower visitors, 15 have been reported as Moringa pollinators by earlier studies (Table 3). Based on the number of flower visitors on weed species, of the 49 weed species, 4 (8.16%) were categorized as highly attractive, 21 as attractive (42.86%) and the remaining 24 (48.98%) as less attractive (Table 4). The maximum number of pollinators was recorded in the weed species *L. aspera* (13) and the minimum in *Euphorbia hirta* (2). The total abundance was higher (69.35%) in Hymenopteran species than in the other orders; for instance, 14% of insects were from the order Lepidoptera and 13.65% from Diptera. Moreover, of the 20 insect species, 6 were dependent on weed species for both nectar and pollen, and the remaining 14 were dependent only for their nectar.

Study of pollinators on selected weeds: The three most visited weed species were common leucas, *L. aspera* (mean no. of visits = 27.70 ± 2.45/day/plant); followed by the African spider flower, *C. gynandra* (mean no. of visits = 20.00 ± 1.05/day/plant); and country mallow, *A. indicum* (mean no. of visits = 15.00 ± 1.89/day/plant) (Table 4). In terms of pollinator species diversity of insect pollinators visiting weeds (Plate 1), 14 different species visited *L. aspera* (Plate 2), followed by 11 species each in *C. gynandra* (Plate 3) and *A. indicum* (Plate 4; Table 5). Social bees (*Apis cerana*, *A. florae* and *Tetrogonula iridipennis*) were the most common visitors to each of the three selected weed species accounting for 57.6% (*A. indicum*), 90% (*C. gynandra*) and 44.3% (*L. aspera*) of visits (Fig. 4). In particular, *T. iridipennis* visited all three weed species, and they were the dominant visitors to *C. gynandra* making more than 75% of all recorded visits to this plant species. For both *A. indicum* and *L. aspera*, Lepidopterans were the second most abundant group of visitors accounting for 30.8% and 38.8%, respectively, of visits. In *C. gynandra*, the recorded visitors were flies (3.8%), solitary bees (3.2%) and butterflies (3%).

Of the three selected weed species, the calculated Shannon diversity index showed that *A. indicum* had the richest diversity (2.07) and *L. aspera* the highest species evenness (0.95); however, the Simpson diversity index was more for *L. aspera* (7.02) followed by *A. indicum* (5.92) and *C. gynandra* (1.72) (Table 6). The interaction pattern between insect pollinators and selected weeds species in the Moringa fields shows that *A. cerena indica* and *A. florae* visited all three selected weed species, while the frequency of visit for *T. iridipennis* was significantly higher in *C. gyandra* (Fig. 4). The frequency of *Zizula hylax* and *Freyeria trochylus* visits was higher than that of other nine different insect species in *L. aspera*.

The insect species that visited the selected weeds were almost the same in all the ten sites, but the number of visits varied slightly between sites (Fig. 5a–j). The five insect species recorded from the family Apidae were observed on *C. gynandra* and *L. aspera*, while only three species were observed on *A. indicum* (Table 5). Although *Tetrogonula iridipennis* visited *C. gynandra* in all the sites, in only one field site it was recorded more number of times. (Fig. 5c). Butterflies and moths were observed more often on *L. aspera* than on any other weed species in all the sites, but the visits of ants were recorded only on *L. aspera* (Fig. 5a–j).

Discussion

The support of insects as pollinators is required for most cultivated crop species for better productivity (Garibaldi et al. 2013) and quality of produce. The diversified group of pollinators keeps the ecosystem stable through pollination services in different plant species having diverse floral characteristics such as colour, size, type, nectar quantity and so on. The abundance and diversity of pollinators in a particular location always depend on the availability of floral resources and their variety. As mentioned earlier, Moringa is highly dependent on insect pollination, which attracts a wide range of insect pollinators. However, since it is a seasonal flowering species, it provides pollen and nectar for only 8–9 months in a year. During this 8- to 9-month window, farmers resort to a high level of field sanitation practices to keep the Moringa field free of weeds (both inside and outside) to obtain higher pod yield. However, during the non-flowering window of 3–4 months, the weed species are left undisturbed as there is no inter-cultivation or any other management practices undertaken by the farmers. In that context, those weed species that co-exist with Moringa are crucial for supporting the flower visitors, including 15 species of pollinators. Anecdotal evidence from local farmers suggests that there has been a reduction in the number and frequency of pollinating insects due to their weed management practices. The farmers' observation is supported by a study in predominantly bee-pollinated crops, namely almond, canola and watermelon – it was reported by Goulson (2003) that the weed management in these crops severely affected pollinator populations. Moreover, studies have recorded an increase in the yield of mango and other crops due to the presence of weed species along with cultivated crops (Gibson et al. 2006; Biesmeijer et al. 2006; Bretagnolle and Gaba 2015; Garratt et al. 2017; Blaix et al. 2018; Blaire M. Kleiman, Koptur, and Jayachandran 2021). However, in the case of Moringa, further studies on the interaction between weed species and primary pollinators of Moringa and its impact on pod yield are necessary.

The overall study results of weed species in Moringa fields showed that the presence of 49 diverse weed species from 16 different families, which have different growth habits, structures and duration, might attract diversified groups of pollinators during the non-flowering season. Of these, 86% are herbaceous plants and 69% are native (B M Kleiman, Koptur, and Jayachandran 2021) and adapted to the region and non-invasive as well. In the present study, a higher percentage of weeds belonged to Asteraceae followed by Amaranthaceae and Malvaceae, and only very few species were from Acanthaceae and Nyctaginaceae; this concurs with the findings of the study by Mahale (2019) in the Western Ghats in India. It is evident from field observation and secondary sources that the floral phenology of more than 69% of the weed species predominantly coincides with the non-flowering window of Moringa.

Overall, a total of 20 flower visitors were observed on the weeds in the Moringa fields. Of these, 15 have been recorded as the pollinators in Moringa by earlier studies (Jyothi, Atluri, and Reddi 1990; Bhatnagar et al. 2018; Sowmiya, Srinivasan, and Saravanan 2018). This indicates the importance of these weed species in supporting those insects during the non-flowering season of Moringa. The insect pollinators recorded on weed species in the Moringa fields belonged to diverse groups; the maximum number of insect pollinators were from Hymenoptera and belonged to the family Apidae. Similar observations were recorded by (Sreebha and Darling Femi 2020; Zameeroddin and Belavadi 2020). Interestingly, both nectar and pollen feeding were observed only among Hymenoptera; the remaining were visiting the weeds for nectar alone.

Moreover, specific weed species–pollinator networks were also observed. Four weed species (*L. aspera*, *C. gynandra*, *A. indicum* and *Acalypha indica*) were highly attractive to the diverse group of pollinators. Overall, the greatest diversity of flower visitors was seen in *A. indicum* and *L. aspera* whereas it was the least in *C. gynandra*. Although the number of flower visitors recorded on *C. gynandra* was similar to that recorded on *A. indicum* and near similar to that on *L. aspera*, the reason for the low diversity index on *C. gynandra* was the dominance of *T. iridipennis* in a single site (Fig. 5c). *Leucas aspera* was recorded as being comparatively more attractive to different group of pollinator species (Rao 2014), especially *A. cerana indica* and *Amegilla zonata*, which are the most dominant pollinators in Moringa (Sowmiya et al. 2018). This is because of the high quantities of nectar in *L. aspera*, which invites many insect pollinators (Kulloli, Chandore, and Aitawade 2011) and could help in good conservation of pollinators (Zameeroddin and Belavadi 2020). *Cleome gynandra* was recorded as an insect pollinator attractant weed species for its nectar and pollen, which are utilized by diverse groups of pollinators from the orders Hymenoptera, Diptera and Lepidoptera (Solomon Raju and Sandhya Rani 2016) (Solomon Raju & Sandhya Rani 2016). The present study recorded visits from 11 species of flower visitors on *C. gynandra*. The importance of *A. indicum* as a pollinator attractant was established based on the frequency of visits made by the diverse species of insect pollinators. This finding was comparable with previous reports wherein researchers recorded *Apis* sp. and *Bembix* sp. as major pollinators; moreover, *A. indicum* attracts different species from Lepidoptera due to its nectar and pollen (Abid et al. 2010).

During the cropping season, when pesticides are sprayed on the main crop, the pollinators may temporarily shift to the flowering weeds on the field margins. In general, farmers prefer to keep their fields free from weeds and use herbicides for that purpose chiefly because knowledge about the weed–pollinator network and interactions, and their positive impact on crop production, is lacking (Christmann et al. 2017). The present investigation has confirmed that the huge diversity of insect pollinators is directly or indirectly associated with the weeds for mutual benefit, and advocates strategy to maintain the floral weeds on the field bunds to establish the diversity of pollinators on fields. (Christmann et al. 2021) also reported the positive effects of wild floral strips on the diversity of pollinators and natural enemies and negative effect on pests on cultivable crops. This interaction is more visible during the non-flowering season of Moringa and helps to retain the biotic balance as reported in a study in the United Kingdom (Marshall et al. 2003).

Conclusion

In summary, it is evident that the seasonal gap in flower availability for Moringa pollinators during the non-flowering window is supplemented by 49 weed species that co-exist with the main crop in the field. The presence of weeds with attractive morphological features (large flowers, shape, colour) and qualitative traits (fragrance, nectar and pollen) which are more or less equivalent to those of the main host plant, that is, Moringa, is required to sustain the pollinator species. Almost 70% of the flowering period of the weed species coincides with the non-flowering season of Moringa. Moreover, three weed species attract Moringa pollinators more than the other species. But the diversity and intensity of pollinator visits vary among these three species. Of the 20 observed flower visitors, 15 were Moringa pollinators and Hymenopterans, and social bees are the dominant ones. Understanding the diversity of weeds, their habits and flowering patterns and the weed–pollinators network is crucial to designing a management strategy for conserving and augmenting pollinators. However, the current intensive weed management practices are not conducive for such biological interactions and outputs. This indicates the necessity of retaining/managing weeds species around Moringa fields in a certain ratio or distance. However, it needs further investigation to develop as an important crop husbandry practice parallel to the model of flower strips.

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Appendices

Table 1. Weed species observed in the Moringa sites during the off-season.

Common name	**Scientific name**	**Family**	**Habit**	**Flowering periodicity**	**Weed type and nativity**
Goat weed	*Ageratum conyzoides*	Asteraceae	Erect	September–June	Non-native, invasive
Floss flower	*Ageratum houstonianum*		Erect	May–November	Non-native, invasive
Spanish needles	*Bidens pilosa*		Perennial herb	October–April	Non-native, priority invasive species
Malay blumea	*Blumea lacera*		Annual herb	January–April	Native
Soft blumea	*Blumea wightiana*		Herb	October–April	Non-native
Siam weed	*Chromolaena odorata*		Perennial shrub	December–March	Non-native, invasive
East Indian globe thistle	*Sphaeranthus indicus*		Herb	October–April	Non-native
Coat buttons	*Tridax procumbens*		Herb	January–December	Non-native, priority invasive species
Bristly star bur	*Acanthospermum hispidum*		Herb or undershrub	January–June	Non-native, priority invasive species
Native rosella	*Abelmoschus ficulneus*	Malvaceae	Undershrub	September–November	Non-native
Musk mallow	*Abelmoschus moschatus*		Herb or undershrub	October–April	Native to Asian region
Florida keys Indian mallow	*Abutilon hirtum*		Herb or undershrub	September–April	Native to tropical region
Country mallow	*Abutilon indicum*		Herb or undershrub	January–October	Native to tropical region
Brazil jute	*Malachra capitata*		Herb	April–December	Non-native
Spine seeded false mallow	*Malvastrum coromandelianum*		Herb	January–December	Non-native
Common wireweed	*Sida acuta*		Herb	September–April	Asian and pacific region, priority invasive species
Heart-leaf sida	*Sida cordifolia*		Undershrub	September–December	Native to Asian region
Red calico plant	*Alternanthera bettzickiana*	Amaranthaceae	Perennial herb	October–February	Non-native, priority invasive species
Smooth joy weed	*Alternanthera paronychioides*		Annual creeping herb	June–August	Non-native, priority invasive species
Khaki weed	*Alternanthera pungens*		Perennial herb	December–March	Non-native, priority invasive species
Spiny pigweed	*Amaranthus spinosus*		Annual or perennial herb	January–December	Non-native, Priority invasive species
Slender amaranth	*Amaranthus viridis*		Annual herb	December–April	Asian region

False amaranth	*Digera arvensis*		Herb	August–September	Asian region
Celandine spider flower	*Cleome chelidonii*	Capparidaceae	Annual herb	January–March	Tropical region
African spider flower	*Cleome gynandra*		Annual herb	January–May	Tropical and sub-tropical regions
Spindle pod	*Cleome monophylla*		Annual herb	September–April	Tropical regions
Tick weed	*Cleome viscosa*		Herb	March–July	Warm and humid habitats
Indian copperleaf	*Acalypha indica*	Euphorbiaceae	Herb	January–December	Tropical regions
Giradol	*Chrozophora plicata*		Annual or biennial herb	February–August	Tropical regions
Three-leaved caper	*Croton bonplandianum*		Herb or subshrub	November–May	Tropical regions, priority invasive species
Asthma herb	*Euphorbia hirta*		Herb	January–December	Tropical regions, priority invasive species
Long leaved alyce clover	*Alysicarpus longifolius*	Fabaceae	Herbs or subshrubs	September–October	Tropical regions – Asia and Africa
Indian joint vetch	*Aeschynomene indica*		Undershrub	September–October	Tropical regions – Asia, Australia and Africa
Trefoil rattle pod	*Crotalaria medicaginea*		Herb	March–August	Tropical and sub-tropical Asia
Lion's ear	*Leonitis nepetaefolia*	Lamiaceae	Herb	November–December	Tropical – Africa and Asia
Common leucas	*Leucas aspera*		Herb	November–February/March	Tropical Asia
White wort	*Leucas martinicensis*		Herb	September–March	Tropical to sub-tropical Africa and Asia
East Indian Jew's mallow	*Corchorus aestuans*	Tiliaceae	Herb	March–October	Tropical and sub-tropical regions
Jew's mallow	*Corchorus olitorius*		Herb	January–December	Tropical regions of Asia and Africa
Bur bush	*Triumfetta rhomboidea*		Herb	April–September	Tropical regions of Asia and Africa
Crown flower	*Calotropis gigantea*	Asclepiadaceae	Large shrub	January–December	Native to Asian region
Swallow-wort	*Calotropis procera*		Evergreen shrub	January–December	Tropical and sub-tropical regions of Asia and Africa
Waterleaf	*Asteracantha longifolia*	Acanthaceae	Herb	September–March	Tropical Asia and Africa
Hairy bittercress	*Cardamine hirsute*	Brassicaceae	Annual or biennial herb	November–December	Europe and North Africa
Red spiderling	*Boerhavia diffusa*	Nyctaginaceae	Herb	January–December	India and Pacific region
Mexican prickly poppy	*Argemone mexicana*	Papaveraceae	Annual herb	January–December	Mexican region, priority invasive species

Coral vine	*Antigonon leptopus*	Polygonaceae	Climber	May–September	Non-native, invasive
Tropical girdle pod	*Mitracarpus villosus*	Rubiaceae	Herb	July–October	Tropical region and Africa
Balloon vine	*Cardiospermum halicacabum*	Sapindaceae	Climber	July–August	Tropical regions

Table 2. Insect pollinators and flower visitors observed on the weeds.

Family	Common name	Scientific name	Species abundance (%)	Total abundance (%)	Order	Forage nature [nectar (N)/pollen (P)/both (NP)]
Apidae	Indian honey bee	*Apis cerana indica*	15.29	52.59	Hymenoptera	NP
	Dwarf honey bee	*Apis florae*	12.47			NP
	Stingless honey bee	*Tetrogonula iridipennis*	18.00			N
	Blue banded bee	*Amegilla zonata*	5.41			NP
	White banded bee	*Amegilla quadrifasciata*	1.41			NP
Halictidae	Sweat bee or Halictid bee	*Pseudopis oxybeloides*	3.88	17.76		NP
	Sweat bee or Halictid bee	*Lasioglossum* sp.	4.71			N
	Halictid wasp	*Ceylalictus bantoonei*	3.06			N
	Halictid wasp	*Ceylalictus perditellus*	3.53			N
	Sweat bee	*Halictus* sp.	2.59			NP
Vespidae	Potter wasp	*Labus pusillus*	2.00	2.00		N
Lycaenidae	Common pierrot	*Castalius rosimon*	3.76	11.53	Lepidoptera	N
	Tiny grass blue	*Zizula hylax*	3.29			N
	Grass jewel	*Freyeria trochylus*	2.35			N
	Metallic cerulean	*Jasmides alecto*	2.12			N
Hesperidae	Ceylon darlet butterfly	*Oriens goloides*	2.47	2.47	Lepidoptera	N
Syrphidae	Hover fly or Syrphid fly	*Paragus* sp.	2.12	3.88	Diptera	N
	Hover fly	*Episyrphus balteatus*	1.76			N
Muscidae	House fly	*Musca domestica*	6.59	6.59		N
Dolichopodidae	Asian long-legged fly	*Condylostyus* sp.	3.18	3.18		N

Table 3. Comparison between the observed flower visitors on weed species and recorded Moringa pollinators from past studies during non-flowering season of Moringa.

S. no.	Name of the flower visitors		Earlier recorded/not recorded on Moringa as pollinators by other researchers	Reference
1	*Apis cerana indica*	Indian honey bee	Recorded	Jyothi et al. 1990; Sowmiya et al. 2018
2	*Apis florae*	Dwarf honey bee	Recorded	Jyothi et al. 1990; Shiwani et al. 2018; Sowmiya et al. 2018
3	*Tetrogonula iridipennis*	Stingless honey bee	Recorded	Jyothi et al. 1990
4	*Amegilla zonata*	Blue banded bee	Recorded	Jyothi et al. 1990; Shiwani et al. 2018; Sowmiya et al. 2018
5	*Amegilla quadrifasciata*	White banded bee	Recorded	Jyothi et al. 1990; Shiwani et al. 2018; Sowmiya et al. 2018
6	*Pseudopis oxybeloides*	Sweat bee or Halictid bee	Recorded	Sowmiya et al. 2018
7	*Lasioglossum* sp.	Sweat bee or Halictid bee	Recorded	Sowmiya et al. 2018
8	*Ceylalictus bantoonei*	Halictid wasp	Recorded	Sowmiya et al. 2018
9	*Ceylalictus perditellus*	Halictid wasp	Recorded	Sowmiya et al. 2018
10	*Halictus* sp.	Sweat bee	Recorded	Sowmiya et al. 2018
11	*Castalius rosimon*	Common pierrot	Not recorded	
12	*Zizula hylax*	Tiny grass blue	Not recorded	
13	*Freyeria trochylus*	Grass jewel	Not recorded	

14	*Jasmides alecto*	Metallic cerulean	Not recorded	
15	*Paragus* sp.	Hover fly or Syrphid fly	Recorded	Sowmiya et al. 2018
16	*Episyrphus balteatus*	Hover fly	Recorded	Sowmiya et al. 2018
17	*Musca domestica*	House fly	Recorded	Sowmiya et al. 2018
18	*Condylostyus* sp.	Asian long-legged fly	Recorded	Sowmiya et al. 2018
19	*Oriens goloides*	Ceylon darlet butterfly	Recorded	Sowmiya et al. 2018
20	*Labus pusillus*	Potter wasp	Not recorded	

Table 4. Attractiveness of weed species to the insect pollinators and flower visitors.

Weed name	Total number of insect pollinator visits	Mean number of insect pollinator visits/day/plant	Number of insect species attracted	Attractive ness	Number of plants observed as (HA/A/LA)
Leucas aspera	277	27.7±2.45	13	Highly attractive	4
Cleome gynandra	200	20.0±1.05	11		
Abutilon indicum	150	15.0±1.89	11		
Acalypha indica	72	7.2±1.03	11		
Sida acuta	52	5.2±0.79	10	Attractive	21
Cleome viscosa	50	5.0±0.82	8		
Sida cordifolia	39	3.9±1.10	8		
Bidens pilosa	100	10.0±1.05	8		
Acanthospermum hispidum	60	6.0±0.82	8		
Boerhavia diffusa	140	14.0±1.25	7		
Ageratum conyzoides	130	13.0±1.25	7		
Abutilon hirtum	69	6.9±1.20	7		
Alternanthera bettzickiana	70	7.0±1.15	7		
Cleome monophylla	60	6.0±0.82	7		
Chromolaena odorata	42	4.2±0.63	7		
Corchorus olitorius	42	4.2±0.79	6		
Amaranthus viridis	81	8.1±0.74	6		
Ageratum houstonianum	71	7.1±1.10	6		
Tridax procumbens	71	7.1±1.10	6		
Antigonon leptopus	50	5.0±0.82	6		
Argemone mexicana	50	5.0±0.67	6		
Crotalaria medicaginea	60	6.0±0.82	6		
Leonitis nepetaefolia	60	6.0±0.94	6		
Malvastrum coromandelianum	51	5.1±1.10	6		
Cleome chelidonii	51	5.1±0.74	6		

Abelmoschus ficulneus	111	11.1±3.03	5	Less attractive	24
Croton bonplandianum	90	9.0±0.67	5		
Triumfetta rhomboidea	71	7.1±1.10	5		
Calotropis procera	71	7.1±0.74	5		
Blumea lacera	50	5.0±0.82	5		
Mitracarpus villosus	50	5.0±1.05	5		
Alysicarpus longifolius	49	4.9±0.74	5		
Leucas martinicensis	41	4.1±0.57	5		
Blumea wightiana	40	4.0±1.15	5		
Corchorus aestuans	40	4.0±1.15	5		
Cardamine hirsute	61	6.1±1.10	5		
Alternanthera paronychioides	61	6.1±0.74	5		
Malachra capitata	91	9.1±0.74	4		
Abelmoschus moschatus	90	9.0±1.33	4		
Amaranthus spinosus	90	9.0±0.67	4		
Chrozophora plicata	70	7.0±1.15	4		
Digera arvensis	61	6.1±0.99	4		
Asteracantha longifolia	60	6.0±0.82	4		
Aeschynomene indica	40	4.0±1.15	4		
Alternanthera pungens	10	10.0±1.05	3		
Sphaeranthus indicus	8	8.0±0.67	3		
Calotropis gigantea	7	7.0±1.15	3		
Cardiospermum halicacabum	0.9	0.9±1.10	3		
Euphorbia hirta	5.1	5.1±1.10	2		

HA: highly attractive; A: attractive; LA: less attractive.

Table 5. Overall visits by predominant insect pollinators on the selected weeds.

Common name	Scientific name	Total number of visits by insects		
		Abutilon indicum	*Cleome gynandra*	*Leucas aspera*
Indian honey bee	*Apis cerana indica*	67±1.49	75±2.88	196±6.00
Dwarf honey bee	*Apis florae*	34±2.01	82±1.62	52±1.23
Stingless honey bee	*Tetrogonula iridipennis*	13±1.06	805±119.79	22±0.79
Blue banded bee	*Amegilla zonata*	–	5±0.53	30±1.05
White banded bee	*Amegilla quadrifasciata*	–	6±0.84	33±1.06
Potter wasp	*Labus pusillus*	8±0.92	–	–
Ant	*Camponotus* sp.	–	–	40±1.94
Sweat bee or Halictid bee	*Pseudopis oxybeloides*	–	–	–
Sweat bee or Halictid bee	*Lasioglossum* sp.	–	–	–
Halictid wasp	*Ceylalictus bantoonei*	–	15±1.18	–
Halictid wasp	*Ceylalictus perditellus*	6±0.84	9±0.88	–
Sweat bee	*Halictus* sp.	–	–	–
Hover fly or Syrphid fly	*Paragus* sp.	–	21±2.13	–
Hoverfly	*Episyrphus balteatus*	–	19±1.60	–
Housefly	*Musca domestica*	–	–	–
Asian long-legged fly	*Condylostyus* sp.	9±1.10	–	–
Common pierrot	*Castalius rosimon*	–	–	38±0.92
Tiny grass blue	*Zizula hylax*	13±1.25	–	45±1.58
Grass jewel	*Freyeria trochylus*	9±0.88	15±1.18	50±1.63
Metallic cerulean	*Jasmides alecto*	–	17±1.34	
Ceylon darlet butterfly	*Oriens goloides*	16±0.84	–	24±0.97
Blue tiger	*Tirumala limniace*	–	–	15±0.85
Tawny coaster	*Acraea violae*	14±1.17		
Common grass yellow	*Eurema hecabe*	–	–	23±1.70
Crimson rose	*Atrophaneura hector*	–	–	17±1.06
Plain tiger	*Danaus chrysippus*	9±0.74	–	24±1.71

The numbers followed by ± were the Standard Deviation of total number of insects visits across the ten sites**.**

Table 6. Diversity of flower visitors on selected weeds.

Diversity index	*Abutilon indicum*	*Cleome gynandra*	*Leucas aspera*
Shannon diversity index	2.07	1.03	1.97
Shannon evenness	0.86	0.42	0.95
Simpson index	5.92	1.72	7.02

Figure 1. Study area.

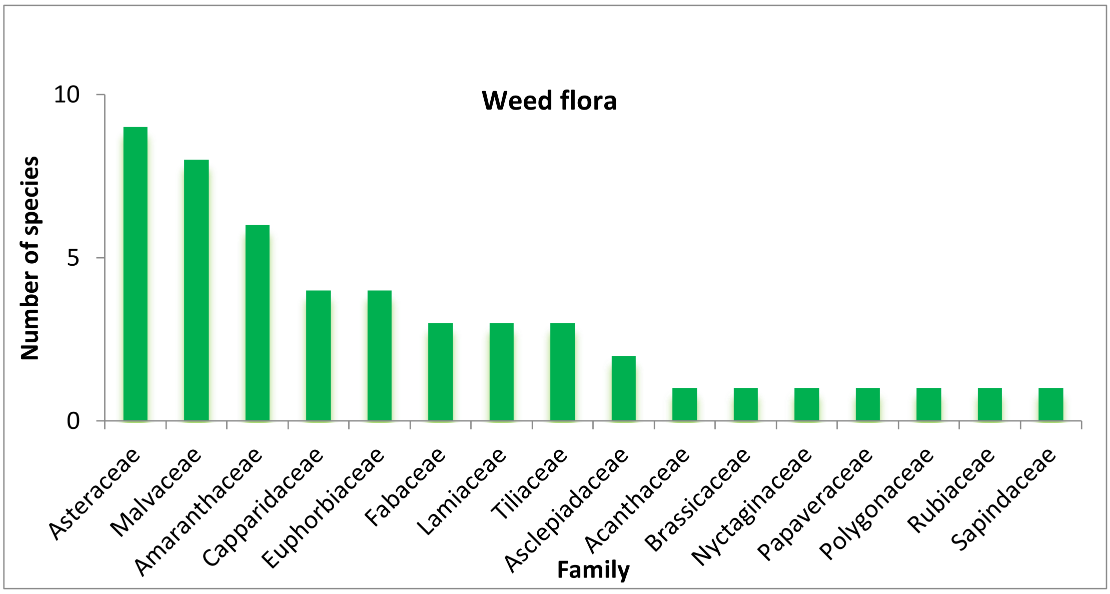


Figure 2. Weed flora in the Moringa field during the off-season.

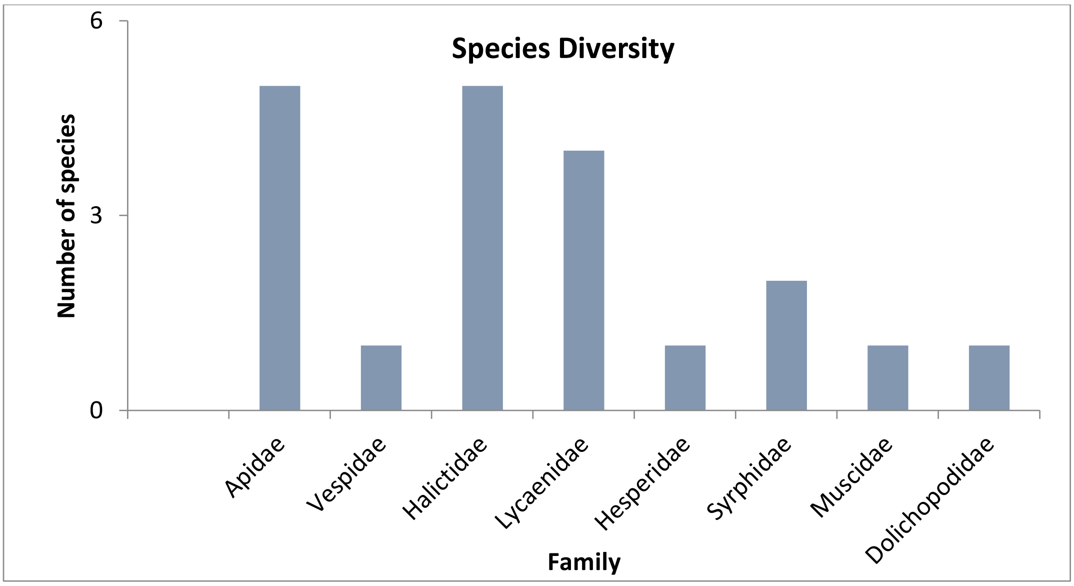


Figure 3. Major insect families observed on the weeds.

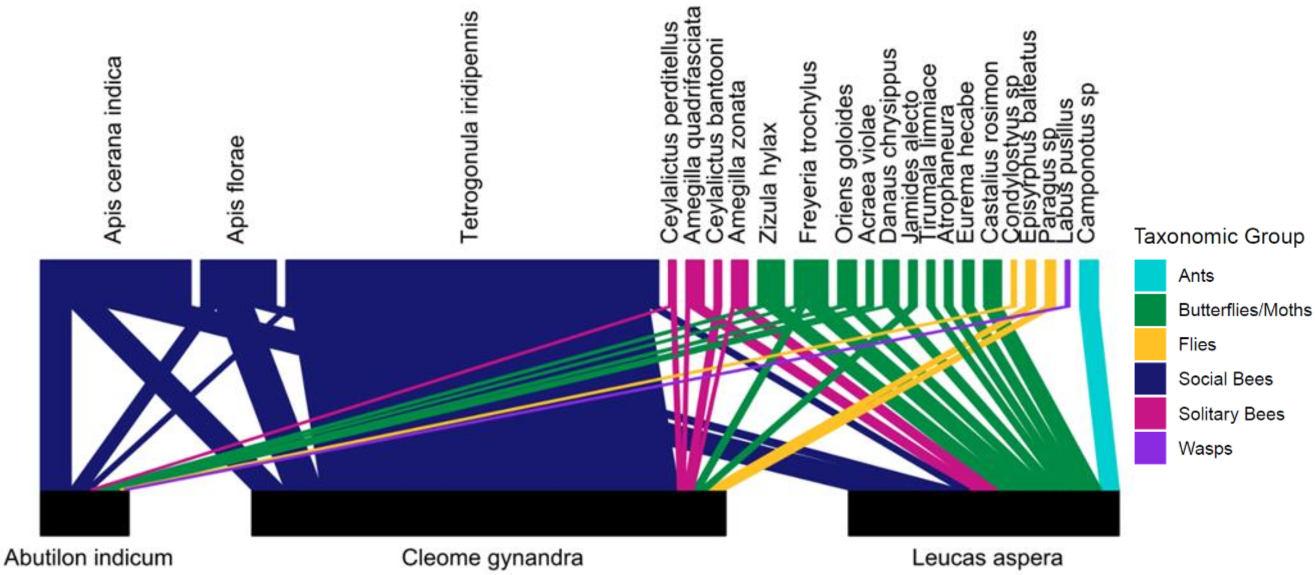


Figure 4. Overall weed–pollinator network for three selected species in Moringa orchards, with weed species on the lower axis (black boxes) and pollinator species on the upper axis (coloured boxes). Width of boxes indicates the relative abundance of flower visitors (upper axis) and weed visits (lower axis).

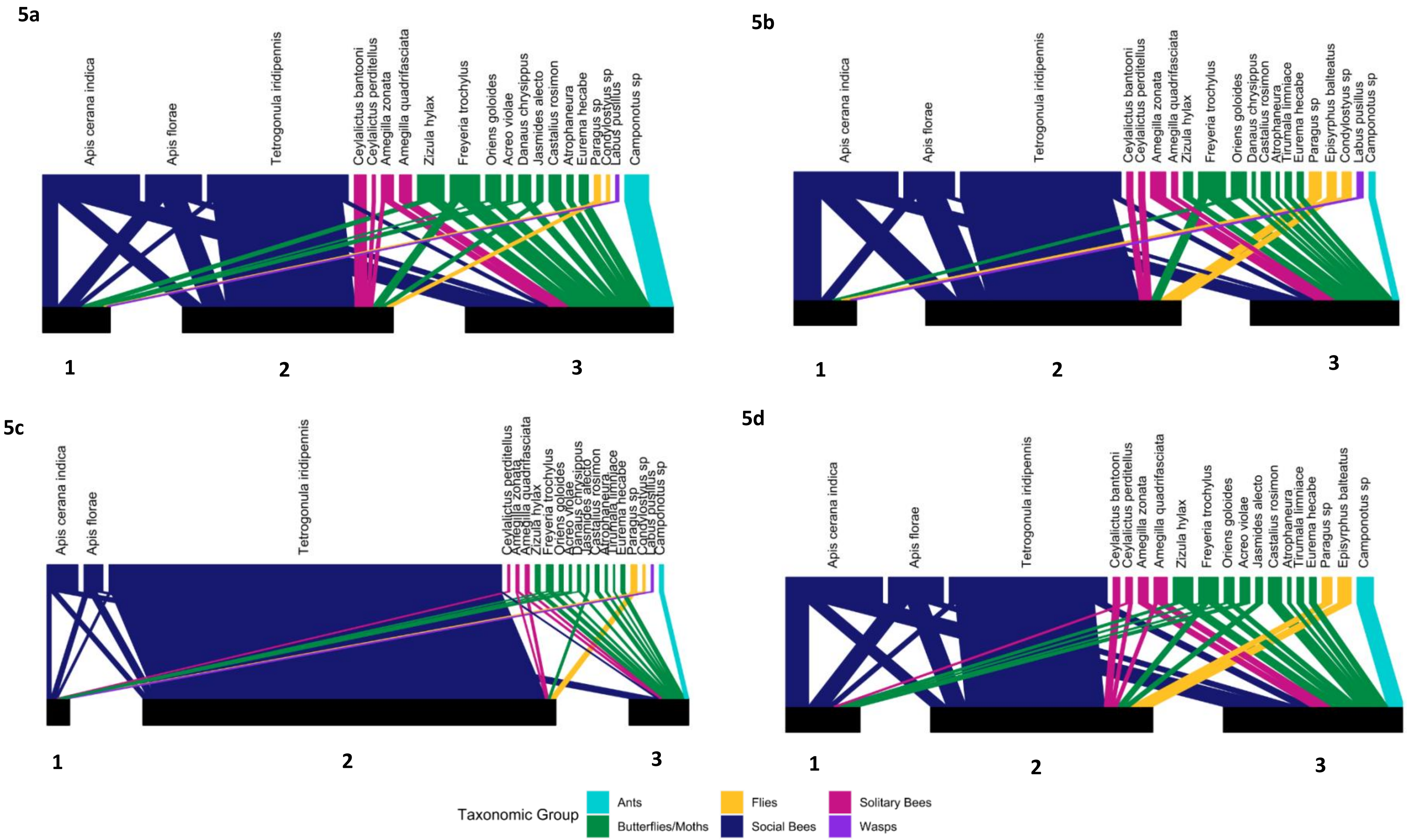
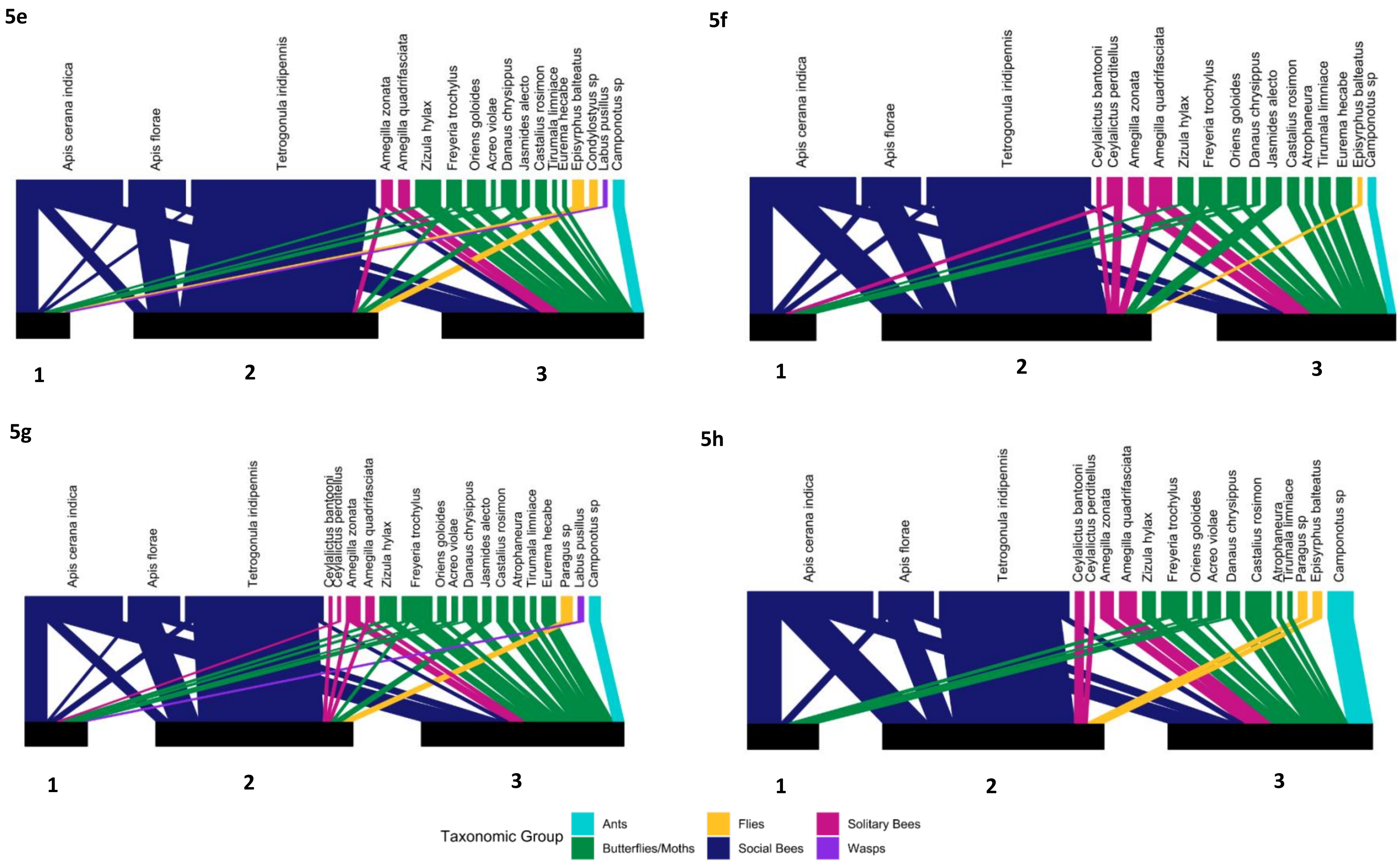


Figure 5 (a–j). Weed–pollinator network for the three selected weed species across individual Moringa fields, with weed species on the lower axis (black boxes) and pollinator species on the upper axis (coloured boxes). Weed species identity as follows: (1) *Abutilon indicum*, (2) *Cleome gynandra* and (3) *Leucas aspera*. Width of boxes indicates the relative abundance of flower visitors (upper axis) and weed visits (lower axis).


5e
Apis cerana indica
Apis florae
Tetrogonula iridipennis
Amegilla zonata
Amegilla quadrifasciata
Zizula hylax
Freyeria trochylus
Oriens goloides
Acreo violae
Danaus chrysippus
Jasmides alecto
Castalius rosimon
Tirumala limniace
Eurema hecabe
Episyrphus balteatus
Condylostylus sp
Labus pusillus
Camponotus sp
1
2
3
5f
Apis cerana indica
Apis florae
Tetrogonula iridipennis
Ceylalictus bantooni
Ceylalictus perditellus
Amegilla zonata
Amegilla quadrifasciata
Zizula hylax
Freyeria trochylus
Oriens goloides
Danaus chrysippus
Jasmides alecto
Castalius rosimon
Atrophaneura
Tirumala limniace
Eurema hecabe
Episyrphus balteatus
Camponotus sp
1
2
3
5g
Apis cerana indica
Apis florae
Tetrogonula iridipennis
Ceylalictus bantooni
Ceylalictus perditellus
Amegilla zonata
Amegilla quadrifasciata
Zizula hylax
Freyeria trochylus
Oriens goloides
Acreo violae
Danaus chrysippus
Jasmides alecto
Castalius rosimon
Atrophaneura
Tirumala limniace
Eurema hecabe
Paragus sp
Labus pusillus
Camponotus sp
1
2
3
5h
Apis cerana indica
Apis florae
Tetrogonula iridipennis
Ceylalictus bantooni
Ceylalictus perditellus
Amegilla zonata
Amegilla quadrifasciata
Zizula hylax
Freyeria trochylus
Oriens goloides
Acreo violae
Danaus chrysippus
Castalius rosimon
Atrophaneura
Tirumala limniace
Paragus sp
Episyrphus balteatus
Camponotus sp
1
2
3
Taxonomic Group
Ants
Butterflies/Moths
Flies
Social Bees
Solitary Bees
Wasps

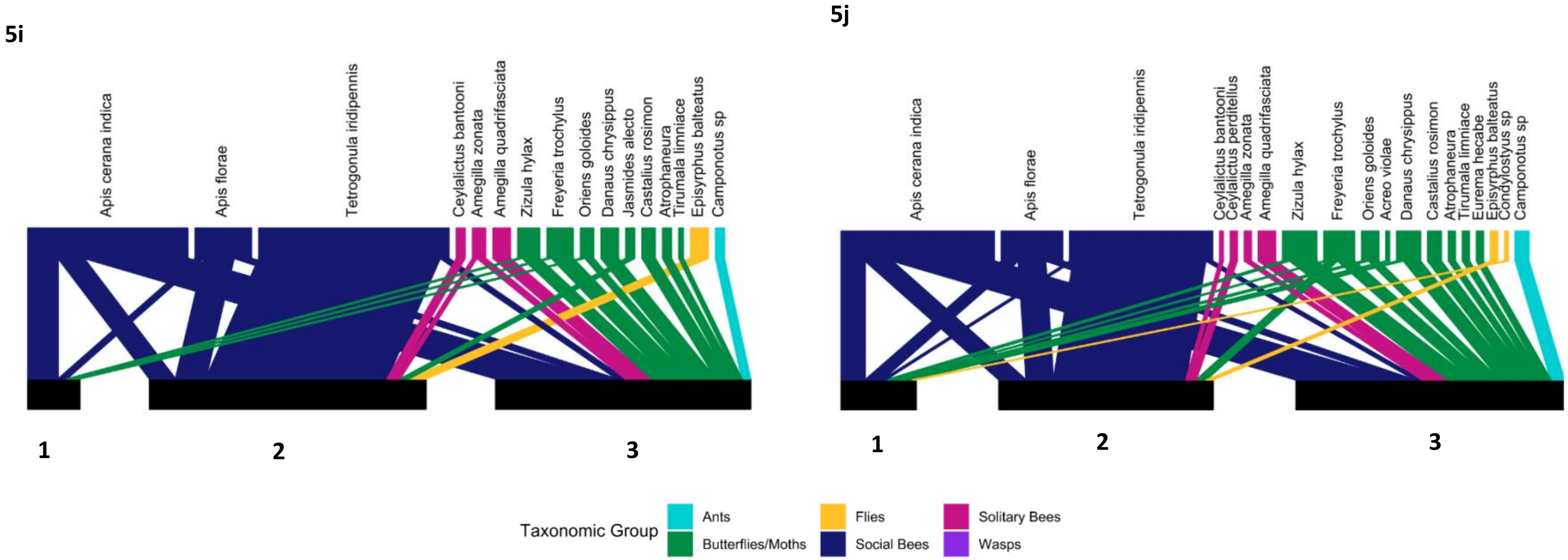

5i
Apis cerana indica
Apis florae
Tetrogonula iridipennis
Ceylalictus bantooni
Amegilla zonata
Amegilla quadrifasciata
Zizula hylax
Freyeria trochylus
Oriens goloides
Danaus chrysippus
Jasmides alecto
Castalius rosimon
Atrophaneura
Tirumala limniace
Episyrphus balteatus
Camponotus sp
1
2
3
5j
Apis cerana indica
Apis florae
Tetrogonula iridipennis
Ceylalictus bantooni
Ceylalictus perditellus
Amegilla zonata
Amegilla quadrifasciata
Zizula hylax
Freyeria trochylus
Oriens goloides
Acreo violae
Danaus chrysippus
Castalius rosimon
Atrophaneura
Tirumala limniace
Eurema hecabe
Episyrphus balteatus
Condylostyus sp
Camponotus sp
1
2
3
Taxonomic Group
Ants
Butterflies/Moths
Flies
Social Bees
Solitary Bees
Wasps

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Plate 1. Moringa field with weeds.

Plate 2. Indian bee visiting *Leucas aspera*.

Plate 3. Blue banded bee visiting *Cleome gynandra*

Plate 4. *Abutilon indicum* in field margins