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Original article

Pesticidal activity of plant extracts as alternatives to synthetic chemical insecticides to fight against *Euscelis* sp. and for preservation of *Apis mellifera* Linnaeus associated to the inflorescences of *Ocimum basilicum* L.

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Abstract

In recent years, researchers have increasingly focused on using secondary compounds from plant extracts as potential alternatives to synthetic insecticides, which can harm biodiversity, including pollinators. This study evaluated the effectiveness of aqueous leaf extracts from *Azadirachta indica* A. Juss., *Carica papaya* L. and *Calotropis procera* (Ait.) R.BR. on the population density of *Euscelis* sp. and the foraging behavior of *Apis mellifera* Linnaeus in a basil (*Ocimum basilicum* L.) field during both the rainy and dry seasons. Trials were carried out using a RCBD with four replications: three plant extracts x one positive control (parastar) x one negative control x four groups of flowers (1: exposed to all pollinators, 2: protected from insects, 3: exposed only to *A. mellifera* and 4: uncovered without insect visits). Results showed that all botanical extracts exhibited insecticidal effects comparable to parastar against *Euscelis* sp. Among the 11 pollinator species recorded, *A. mellifera* was the most frequent visitor, foraging throughout the day with activity peaking at 10–11 AM during the dry season and 12–1 PM during the rainy season. The highest abundance of *A. mellifera* per 1000 flowers was recorded in the *C. papaya* treatment, which significantly improved seed yield. These results suggest that the tested botanical extracts are promising eco-friendly alternatives for integrated pest management, helping to reduce the risks of synthetic insecticides to pollinators and enhance basil seed production.

Keywords: aqueous botanical extract, *Apis mellifera*, foraging behavior, *Euscelis* sp., *Ocimum basilicum*

Introduction

Ocimum basilicum (Lamiaceae), commonly known as sweet basil, is a widely cultivated annual herb in tropical and subtropical regions (Smitha *et al*. 2014). In Cameroon, its leaves are traditionally used in soups, stews, and meats, while its seeds are consumed for their antioxidant and nutritional properties, including their ability to help regulate body weight, blood sugar, and lipid levels (Arivuchudar *et al*. 2022). The increasing demand for basil has turned it into a valuable cash crop in the region.

Basil is typically propagated by seeds, but high cross-pollination rates lead to seed deterioration over time, requiring frequent renewal for optimal yields (Smitha *et al*.

2014). Insect pests including thrips, aphids, leaf folders, lace bugs, whiteflies, mites, beetles, and jassids are major production constraints, significantly affecting productivity (Namvong and Chongrattanameteekul 2015; Katbeh-Bader *et al*. 2019; Kumar *et al*. 2022). Farmers commonly resort to synthetic pesticides, but improper use, often due to lack of training, poses serious risks to human health and the environment (Abang *et al*. 2013; Tudi *et al*. 2021; Gumber 2022). Furthermore, these chemicals disrupt beneficial insects like pollinators, negatively affecting crop pollination and yields (Chakraborti and Sarkar 2011; Baskar *et al*. 2017).

To promote sustainable pest management, recent research has focused on plant-derived insecticides and DNA-based approaches (Parolin *et al*. 2012; El-Wakeil 2013; Oberemok *et al*. 2015; Prabha *et al*. 2016; Adamou *et al*. 2022; Abdullah and El-Rokh 2023; da Silva *et al*. 2023). Botanical products such as essential oils and crude extracts are typically biodegradable and have low toxicity to non-target organisms, including pollinators and mammals (Bakkali *et al*. 2008; Ndakidemi *et al*. 2016).

Plants such as *Azadirachta indica* A. Juss., *Carica papaya* L., and *Calotropis procera* (Ait.) R. Br., which are common in northern Cameroon, have well-documented insecticidal properties (Gnago *et al*. 2010; Tahiri 2012; Barry *et al*. 2017; Ngom *et al*. 2020). However, their effects on pollinators remain underexplored. This study, therefore, evaluated the toxicity of aqueous extracts from these plants on the pest *Euscelis* sp. and the foraging behavior of the pollinator *Apis mellifera* in *O. basilicum* fields.

Materials and Methods

Study site and biological materials

The study was conducted during the rainy season (2019) and the dry season (2020) in Bocklé (09° 17'29.33"N; 13° 25'3.75"E; 170 m elevation), located in the Benoué Division, Garoua, North Region of Cameroon. This area belongs to the Sudano-Sahelian ecological zone, characterized by a Sudanian climate with two distinct seasons: a rainy season (April to October) and a dry season (November to March). The region receives an annual rainfall ranging from 400 to 900 mm, mainly between July and October, and has an average annual temperature of 28°C (Djongyang 2022).

Ocimum basilicum L. seeds were purchased from a local agri-supply store in Garoua. Fresh leaves of *Azadirachta indica* A. Juss., *Carica papaya* L., and *Calotropis procera* (Ait.) R. Br. were collected from Laïnde, a locality in Garoua. The synthetic insecticide parastar® [formulated with 10% active ingredients: 20 $g.l^{-1}$ imidacloprid and 20 $g.l^{-1}$ lambda-cyhalothrin (40EC 535/10/IN)] approved in Cameroon and commonly used by farmers (Sonchieu *et al*. 2018) was used as the positive control.

Experimental field

Seedlings and transplantation

On July 30, 2019, and November 5, 2019, the soil was thoroughly tilled to prepare plots measuring 1m x 2m. *Ocimum basilicum* seeds were sown on the soil surface, lightly raked in, watered, and covered with straw to maintain moisture and support germination. Watering was done twice daily (morning and evening) until the seedlings were ready for transplantation.

Sixty seedlings, at least two weeks old, were transplanted into each subplot of the main experimental field. Plant spacing was 36 cm within rows and 50 cm between rows. Transplantation was done in the evening to reduce transplant shock.

Experimental design

The trials were conducted from August to October 2019 (rainy season) and from November 2019 to February 2020 (dry season). A randomized complete block design (RCBD) with four replications was used. The total experimental area (19 × 23 m^2) was divided into 44 plots (4 × 3.5 m^2), separated by 1-meter alleys.

Once flower buds appeared, 540 buds were randomly selected and grouped as follows:

- **Group 1:** 120 flowers left open and exposed to all insect pollinators;
- **Group 2:** 120 flowers covered with gauze bags to exclude all insect visits;
- **Group 3:** 200 buds covered with gauze bags, delicately opened at anthesis for 1–10 minutes to allow exclusive visits by *A. mellifera*, then re-covered;

- **Group 4:** 100 buds covered, then briefly uncovered at bloom stage (1–10 minutes) and re-covered without any insect visits. Manual monitoring ensured no contact with insects or other organisms.

The experimental design was comprised of: 3 plant extracts x 1 standard synthetic insecticide x 1 control x 4 labelled groups of flowers.

Each treatment (three botanical extracts, one synthetic insecticide, and one control) was applied across all four flower groups.

Formulation of insecticide products and application

Fresh leaves of *A. indica*, *C. papaya*, and *Ca. procera* were processed into aqueous extracts using the method described by Gupta *et al*. (2020). For each species, 400 g of fresh leaves were crushed and macerated in 4 l of water for 12 hours, then filtered through a 0.2 mm mesh.

To determine the concentration of plant material in one liter of extract, one liter of each filtrate was evaporated at 100°C in pre-weighed porcelain containers. The weight of the dried extract was obtained by subtracting the tare weight of the container.

For field application, the extracts were diluted to a 10% concentration. Parastar was used at the recommended dose: 3 mL of product per 15 l of water. Manual sprayers, each assigned to a specific treatment, were calibrated, and products were applied at a rate of 714 $l.ha^{-1}$. Spraying was performed between 5:00 and 6:00 PM every five days, from transplanting until fruit maturation.

Data collection

Insect specimen collection and identification

Insect visitors to *O. basilicum* flowers were monitored weekly, starting one week after transplantation. Observations occurred between 6:30 and 10:30 AM.

Thirty-two randomly selected plants per subplot were inspected. The number of morphologically similar insects was recorded, along with their position (flower, leaf, or stem). Insects were captured using entomological forceps (larvae) or nets (adults), preserved in 70% ethanol or papillotes (for Lepidoptera), and labeled by treatment.

Insects were identified using a stereomicroscope, taxonomic keys, and illustrated references (Lecoq 2010; Brailovsky 2014; Gourmel 2014; Tronquet 2014; Zettler *et al*. 2016; Albrecht 2017).

The frequency of each species (Fi) was calculated using:

$Fi = (Vi / VI) \times 100$,

where Vi = number of visits by species i, and VI = total number of visits by all insect species.

Assessment of botanical extracts impact on *Euscelis* sp. dynamics

Plots were randomly assigned to receive one of three botanical treatments, parastar, or water (control), with four replications per treatment. Weekly counts of *Euscelis* sp. were conducted from:

- August 29 to October 17, 2019 (rainy season)
- December 1, 2019 to January 19, 2020 (dry season)

Observations were made on 32 plants per subplot.

Evaluation of the foraging activity of *Apis mellifera* on *Ocimum basilicum* flowers under different treatments

The foraging activity of *A. mellifera* was monitored on flowers that were left exposed to all insect pollinators (Group 1) during both the rainy and dry seasons. Observations were carried out daily from 6:00 AM to 5:00 PM at one-hour intervals (6:00 AM-7:00 AM, 8:00 AM-9:00 AM, 10:00 AM-11:00 AM, 12:00 PM-1:00 PM, 2:00 PM-3:00 PM, 4:00 PM-5:00 PM). The observation period extended from the day of first flower opening (October 1, 2019 for the rainy season and January 9, 2020 for the dry season) to the day of final flower senescence (October 20, 2019 for the rainy season and January 27, 2020 for the dry season).

The frequency of *A. mellifera* visits was calculated using the following formula:

$Fx = (Vx / Vi) \times 100$

where:

- F_x = frequency of *A. mellifera* visits (%);
- V_x = number of *A. mellifera* visits on exposed flowers

- V_i = total number of insect visits on flowers from the same treatment group.

To assess foraging behavior, the duration of nectar and/or pollen collection by each *A. mellifera* worker was recorded across all treatments. Observations were made at six daily time intervals, from 7:00 AM to 6:00 PM, at one-hour intervals.

Foraging speed (Vb) was determined as the number of flowers visited per minute, following the method of Jacob-Remacle (1989):

$Vb = Fi / di \times 60$,

Where:

- F_i = number of flowers visited
- d_i = time in seconds spent collecting floral resources

Additionally, the number of *A. mellifera* individuals simultaneously foraging on a single flower was recorded and used to extrapolate bee abundance per 1,000 flowers.

Assessment of biotic and abiotic factors influencing the foraging activity of *Apis mellifera* on *Ocimum basilicum*

To evaluate the influence of biotic and abiotic factors on *A. mellifera* foraging, direct observations were made of potential disruptions caused by competitors and/or predators, as well as bee flower constancy. Temperature and relative humidity were recorded every 30 minutes using a digital RH/TEMP data logger (EL-USB-2+; LASCAR Electronics, China).

Assessment of the contribution of extracts and *Apis mellifera* to the quantitative and qualitative seed production of *Ocimum basilicum*

To determine the contribution of insect pollinators and the different treatments to seed production, the fruiting index (IFr) and fruiting rate (Fr) were calculated as follows:

$IFr = (F1/F2)$ and $Fr = (F1/F2)*100$

Where:

- F_1 = number of fruits formed;
- F_2 = number of initially labeled flowers.

The outcrossing rate (TC) was calculated following the method of Demarly (1977):

TC = {[(IfrX - IfrY)/IfrX] x 100},

Where:

- IFr_X = mean fruiting index of flowers exposed to all insect pollinators (Group 1);
- IFr_Y = mean fruiting index of protected flowers (Group 2).

The rate of self-pollination in the broad sense (TA) was then calculated as:

TA = 100 – TC

The combined effect of insect pollinators and each treatment (botanical extract or parastar) on fruiting (TFr), as well as the specific effect of *A. mellifera* (AmFr), were calculated using:

TFr = {[(Fr1 – Fr4)/(Fr1 + Fr2 – Fr4)] * 100}

Where:

- Fr_1 = fruiting rate of Group 1 (exposed to all insect pollinators);
- Fr_2 = fruiting rate of Group 2 (protected);
- Fr_4 = fruiting rate of Group 4 (uncovered without insect visits).

AmFri = (Fr3 – Fr4) x 100

Where:

- Fr_3 = fruiting rate of Group 3 (flowers visited exclusively by *A. mellifera*).

To assess seed quality, 15 plants per treatment were randomly selected. Mature capsules were manually opened, and normal and abnormal seeds were counted. The percentage of normal seeds (%NS) was calculated as:

NS (%) = (Number of normal seeds/Total seeds)*100.

For seed yield determination, mature flowering stems were harvested just below the last flower bud. They were air-dried in a well-ventilated area. Seeds were manually rubbed from the flower heads and cleaned using a fine-mesh sieve. Cleaned seeds were weighed using a digital balance, and seed yield was expressed in kg/ha by dividing the total seed weight per plot by the plot area (14.5 m^2).

Statistical data analysis

Data were analyzed using SPSS v20. Most variables were log-transformed to meet statistical assumptions before applying ANOVA, followed by Tukey's HSD test.

ANOVA was used for insect abundance, foraging behavior, fruiting metrics, and seed quality. Student's t-test compared seasonal quantitative data, while the chi-square test assessed qualitative differences. Correlations between *A. mellifera* visits and flower availability were evaluated using Pearson or Spearman coefficients, based on data distribution.

Results

Insect pests recorded on *Ocimum basilicum*

A total of 497 and 392 visits, comprising 18 and 11 species, were recorded on *O. basilicum* during the rainy and dry seasons, respectively. *Euscelis* sp. was the most abundant pest, with 91 (18.73%) and 80 (20.40%) occurrences during the rainy and dry seasons, respectively (Table 1). However, its abundance did not significantly differ between the two seasons ($\chi^2 = 0.62$; df = 1; $p = 0.335$).

Notably, *Borneogryllacris* sp. was more prevalent during the rainy season, while *Neoconocephalus* sp. was more abundant during the dry season.

Toxicity of botanical extracts on *Euscelis* sp. in basil field

Euscelis sp. was observed in the basil field from 15 to 36 days after transplantation during the rainy season and from 20 to 69 days during the dry season (Fig. 1). Peak pest density occurred at 29 days (rainy season) and 27 days (dry season). At 29 days after transplantation during the rainy season, both *Calotropis procera* and *Carica papaya* significantly reduced the population of *Euscelis* sp. ($F_{4,15} = 7.68$; $p = 0.001$), comparable to the standard reference insecticide, parastar. At 36 days, *A. indica* also showed equivalent efficacy to parastar ($p = 0.973$, pairwise comparison).

During the dry season, both *Ca. procera* and *A. indica* significantly reduced pest numbers at 27 days ($F_{4,15} = 13.91$; $p < 0.001$), effectively suppressing *Euscelis* sp. At 41 days, the effectiveness of *C. papaya* was similar to that of parastar ($p = 0.946$, pairwise comparison). However, from 48 to 69 days, none of the treatments significantly affected pest abundance ($F_{4,15} = 0.58\text{-}1.38$; $p = 0.288\text{-}0.681$).

Insect pollinators of *Ocimum basilicum*

Three insect orders and two families per order were recorded during the dry season: Diptera (Muscidae and Syrphidae), Hymenoptera (Apidae and Megachilidae) and Lepidoptera (Nymphalidae and Pieridae) (Table 2). Species richness was highest for Apidae (5 species), followed by Nymphalidae (2), with one species per the other families. During the rainy season, pollinators consisted of three Lepidoptera species (*Acrea acerate* Hewitson, *Hypolimnas misippus* Linnaeus and *Mylothris chloris* Fabricius) and *A. mellifera* (Hymenoptera: Apidae). *Apis melliffera* was the dominant species in both seasons, accounting for 74.82% and 50.40% of visits in the rainy and dry seasons, respectively. Its abundance was significantly higher in the dry season (375 visits) than in the rainy season (312 visits) ($\chi 2 = 65.95$; df = 1; $p < 0.001$).

Three Apidae species (*Amegilla atrocincta*, *A. mellifera*, *Xylocopa olivacea*) collected both nectar and pollen, while the remaining eight species collected only nectar.

The visit frequency of *A. mellifera* was positively correlated with the number of open flowers, regardless of treatment. During the dry season, Pearson correlation coefficients ranged from r = 0.388 to 0.437, with $p < 0.05$. In the rainy season, significant correlations were observed for the control (r = 0.310; p = 0.016) and *C. papaya* (r = 0.461; $p < 0.001$). Spearman's correlations were more appropriate for *Ca. procera* (ρ = 0.355; p = 0.005), *A. indica* (ρ = 0.379; p = 0.003), and parastar (ρ = 0.336; p = 0.009).

Foraging activity of *Apis mellifera*

Apis mellifera foraging activity varied throughout the day, peaking between 10:00–11:00 AM during the rainy season and 12:00–1:00 PM during the dry season (Figure 2). At peak foraging times, *C. papaya* treatment attracted significantly more bees than the control or other treatments, while the synthetic insecticide was consistently repellent ($F_{4,45} = 3.65$; p = 0.012 rainy season; $F_{4,30} = 2.65$; p = 0.05 dry season).

Optimal environmental conditions for foraging were recorded at 34.1 ± 1.4°C (rainy season) and 34.1 ± 0.9°C (dry season) for temperature, and 75.9 ± 9.8% (rainy) and 43.5 ± 2.2% (dry) for relative humidity.

The mean duration of nectar and pollen collection was significantly longer in botanical treatments than in untreated or parastar-treated plants across both seasons ($F_{4,168}$ = 3.08–18.93; p < 0.05–0.001). On average, nectar collection lasted 7.67 seconds and pollen collection 3.97 seconds in the rainy season, increasing to 8.6 and 4.53 seconds, respectively, during the dry season (Table 3).

Abundance of *Apis mellifera* foraging on basil flowers

During the dry season, the number of *A. mellifera* individuals foraging per 1,000 flowers was more than four times higher than during the rainy season (Table 4). While treatment effects on bee abundance were not significant in the rainy season, *C. papaya* and *Ca. procera* treatments significantly increased bee foraging during the dry season ($F_{4,168} = 5.90$; $p < 0.001$).

Foraging speed of *Apis mellifera* on *Ocimum basilicum* flowers

In treatments with *C. papaya*, *Ca. procera*, and untreated plants, *A. mellifera* foraged significantly faster during the rainy season than in the dry season ($t = 2.38–3.68$; $p = 0.000–0.043$) (Table 5). The highest foraging speeds were recorded on *C. papaya* and *A. indica* treatments in both seasons.

Biotic and abiotic factors influencing *Apis mellifera* foraging

During observation periods, *A. mellifera* also visited flowers of neighboring plant species, including *Abelmoschus esculentus*, *Allium cepa*, *Commelina diffusa*, *Corchorus olitorius*, *Gossypium hirsutum*, *Hibiscus sabdariffa*, *Psidium guajava*, *Solanum nigrum*, and *Vigna unguiculata*.

Foraging activity was occasionally disrupted by biotic competitors and abiotic factors such as rain and wind. During the rainy season, 18 of 312 bee visits (5.76%) were interrupted by rain, while in the dry season, 25 (6.66%) were interrupted by *X. olivacea* and 20 (5.33%) by intraspecific competition.

Contribution of extracts and *Apis mellifera* to basil seed production

Extracts, particularly *A. indica*, significantly increased the fruiting rate of insect-pollinated *O. basilicum* in both seasons ($F_{4,115} = 4.70$; $p = 0.009$ rainy; $F_{4,115} = 2.55$; $p = 0.043$ dry) (Table 6). During the dry season, all extracts improved the percentage of normal seeds compared to untreated plants ($F_{4,115}$ = 4.58; p = 0.002), matching the performance of the positive control.

In the rainy season, *C. papaya* significantly increased seed quality in protected flowers ($F_{4,115}$ = 5.60; p < 0.001), surpassing both *A. indica* and *C. procera*. The latter two were statistically equivalent to parastar (p = 0.657) (Table 7).

Apis mellifera's exclusive contribution to fruiting was significant in extract-treated flowers in both seasons ($F_{4,115}$ = 8.52; p < 0.001). The outcrossing rate of *O. basilicum* was highest under *A. indica* treatment ($F_{4,115}$ = 3.48; p = 0.010 rainy; $F_{4,115}$ = 8.01; p < 0.001 dry). *Calotropis procera* also increased outcrossing during the dry season.

Although differences in self-pollination rate (TA) were not significant in the rainy season (p = 0.140), *C. papaya* yielded the highest TA during the dry season.

Basil seed yield

During the rainy season, seed yields from botanical extract treatments were comparable to those from the synthetic insecticide and significantly higher than untreated controls ($F_{4,15}$ = 4.65; p = 0.012) (Table 8). Notably, *C. papaya* extract significantly improved seed yield compared to both parastar and the control ($F_{4,15}$ = 11.65; p < 0.001). During the dry season, both *A. indica* (t = 3.35) and *Ca. procera* (t = 3.38) significantly enhanced seed yield (p = 0.015).

Discussion

The results of this study highlight the foraging patterns of *Apis mellifera* on *Ocimum basilicum* and their sensitivity to environmental factors and pest control strategies. The study showed that the leaves particularly, the stems and rarely flowers of *O. basilicum* attracted 18 insect pest species during the rainy season at Boklé, Garoua Cameroon. This result can be explained by the fact that leaves are a primary food source for many insects, as they are rich in nutrients (Gullan and Cranston 2005). Among the recorded insect pests, *Euscelis* sp. occurred occasionally in both the rainy and dry seasons, while *Neoconocephalus* sp. and *Dysdercus delauneyi* Lethierry were exclusively occasional invaders during the dry season, following the classification of Bigot and Bodot (1973). The remaining species were sporadic. During the dry season, 11 species were associated with *O. basilicum*, including the three occasional invaders and the remaining sporadic ones. In contrast, 18 species were recorded during the rainy season. The greater insect diversity during the rainy season is likely due to the optimal microenvironmental conditions of precipitation and humidity, which favor the growth of other host plants for these insect pests. Ramos-Robles *et al*. (2023) reported similar observations. In contrast to insect pests, the diversity of insect pollinators associated with *O. basilicum* was greater during the dry season. This is probably due to the disappearance of seasonal flowering plants that grow exclusively during the wet season. *A. mellifera,* attracted to both nectar and pollen, was a constant pollinator species in both the wet and dry seasons. This consistent presence likely stems from the high attractiveness of basil's nectar and pollen to this bee species. Hellen *et al*. (2018) made the same observations in Kenya. *Acrea acerata* and *Megachile* sp. attracted by nectar were occasional pollinators, respectively, in the rainy and dry season.

Pest control measures are crucial during the wet season due to the increased diversity and abundance of insect pests. This study found that aqueous leaf extracts of *Carica papaya*, *Calotropis procera*, and *Azadirachta indica* exhibited insecticidal properties against *Euscelis* sp. Previous research has reported similar insecticidal effects of these plants against other insect pests. Azadirachtin derived from the Indian plant *A. indica* showed high efficacy against arthropod pest species (Kilani-Morakchi *et al*. 2021). Results obtained by Souza *et al*. (2023) indicated that the organic extract of *Ca. procera* possesses many useful properties to control *Spodoptera frugiperda*. According to Gupta *et al*. (2020), the aqueous leaf extract of *C. papaya* is a potential candidate for the development of bio insecticides. In the present investigation, the potential of these botanical extracts was similar to that of the harmful standard synthetic insecticide parastar, hence they may be adopted as safe alternatives.

During the observations presented here, foragers approaching a flower would often briefly touch or hover over it before flying away. This discriminatory behavior suggests that bees are able to smell the nectar and select the most rewarding flowers. The extracts tested in this study did not negatively impact the strong relationship between worker bees and *O. basilicum* flowers; some extracts, such as those from *C. papaya* and *Ca. procera*, even increased bee activity. In fact, when collecting nectar, odorants influence positively *A. mellifera* perception of sweetness (Pel *et al*. 2023). The increased bee activity observed with *C. papaya* and *Ca. procera* extracts could be attributed to their volatile compounds, which enhance honeybees' perception of sweetness. Therefore, it is reasonable to assume that some volatile compounds in these extracts play a role in the flower-pollinator relationship, potentially enhancing *O. basilicum* pollination. *Carica papaya* leaf-derived compounds, such as kaempferol, quercetin, p-coumaric acid, and gallic acid (Ikram *et al*. 2015), have been reported to have beneficial impacts on bee health (Geldert *et al*. 2021). In contrast, the active compound imidacloprid, found in the synthetic insecticide parastar, has been reported to be highly toxic to honeybees (Kot *et al*. 2023). It can also induce memory impairments (Lin *et al*. 2023) and decrease honeybee longevity (Raymann *et al*. 2018).

This study investigated the foraging behavior of *A. mellifera* bees in relation to *C. papaya* and a synthetic insecticide. The findings suggest that *C. papaya* is a highly attractive food source for bees, especially during peak foraging periods, both in the rainy and dry seasons. This was demonstrated by significantly higher bee visitation rates to *C. papaya* than to other treatments and the control group. Conversely, the synthetic insecticide was consistently repellent to the bees.

The study also identified the optimal environmental conditions for bee activity: 34.1°C and 75.9% relative humidity in the rainy season, and 34.1°C and 43.5% relative humidity in the dry season. These factors likely reflect the daily periods of greater availability of floral resources, coinciding with the highest number of open flowers and optimal temperatures (34.1°C). According to Pacini and Nepi (2007) low relative humidity leads to fast evaporation of nectar water, and thus to a high sugar concentration, while conversely high relative humidity limits evaporation of nectar water and maintains a lower sugar concentration. *Apis mellifera* preferred nectar with high sugar concentration (Moreno and Arenas 2024). These findings provide valuable insights into the factors influencing bee foraging behavior and their preference for *C. papaya* as a food source. Importantly, the study highlighted the potential of *C. papaya* as a natural alternative to synthetic insecticides. Its attractiveness to bees, coupled with its potential for repelling pests like *Euscelis* sp., suggests a promising avenue for developing environmentally friendly pest control strategies that support both pollinator health and agricultural productivity.

The increased foraging speed of *A. mellifera* during the rainy season compared to the dry season may be attributed to the greater diversity and abundance of food sources during the wet season. The greater diversity and abundance of food sources, coupled with favorable environmental conditions, could drive bees to forage more efficiently and quickly. The highest foraging speeds observed on treatments with *C. papaya* and *A. indica* may be partly explained by the attractiveness of these plant extracts to both *A. mellifera* and other insect competitors. Previous researchers (Kovac and Stabentheiner 2011) reported similar findings. However, the observed differences in foraging speed between the seasons raise interesting questions about the influence of climate change on bee behavior. As temperatures rise and rainfall patterns shift, understanding the factors driving foraging speed and resource availability is crucial for ensuring that bee populations can adapt and thrive.

While this study focused on *O. basilicum*, it is crucial to acknowledge the influence of surrounding plant species on bee foraging behavior. This suggests a complex interplay between local plant communities and bee foraging preferences as reported by Mramba (2025). The observation of biotic factors, like competition with other arthropods for nectar and pollen, underscores the challenges bees face in securing resources. Goulson *et al*. (2015) highlight that kind of competition in their investigation. Intriguingly, their study found that intraspecific competition also played a role, indicating that resource scarcity can drive competition even within the same bee species.

Abiotic factors, such as rain and wind, were also observed to disrupt foraging activities. While rain had a more significant impact during the rainy season, wind and interspecific competition presented challenges during the dry season. This emphasizes the importance of considering both biotic and abiotic factors in understanding bee foraging dynamics. The findings highlight the need for further research to understand the complex interplay of these factors and their impact on bee colony health and productivity. This knowledge is crucial for developing effective strategies to conserve and promote bee populations in diverse landscapes.

The study provides strong evidence that botanical extracts can significantly enhance basil seed production, potentially through both direct effects on plant development and indirect effects on insect pollination. The results indicate that *A. indica* extract consistently enhanced fruiting rates in *O. basilicum* across both the rainy and dry seasons, suggesting its potential role as a general stimulant for flowering. Interestingly, while all tested extracts significantly improved seed quality during the dry season, no such effect was observed during the rainy season, pointing to possible seasonal variation in extract efficacy. Notably, during the rainy season, treatments combining insect pollinators with either *Ca. procera* or *C. papaya* extracts led to significantly higher fruiting rates than the control, suggesting a synergistic interaction between plant extracts and pollinator activity. These findings are consistent with those reported by Adamou *et al*. (2022). The significant contribution of *A. mellifera* specifically to fruiting in extract-treated plants further supports the idea that extracts may enhance pollinator attraction or effectiveness. *A. indica* significantly increased the outcrossing rate in basil, suggesting it may promote cross-pollination, potentially leading to greater genetic diversity and stronger offspring. This effect was observed in both seasons, highlighting the consistent influence of *A. indica* on pollination dynamics.

Extracts generally increased seed yield compared to untreated basil, demonstrating their potential to enhance overall production. Notably, *C. papaya* extract significantly improved seed yield during the rainy season, indicating its specific effectiveness under those conditions. During the dry season, both *A. indica* and *Ca. procera* significantly boosted yield, suggesting their adaptability to different environmental conditions.

However, a key limitation of this study is that it was conducted at a single location and over only one rainy and one dry season. This limited temporal and geographic scope may restrict the generalizability of the findings, as insect activity, plant responses, and environmental conditions can vary significantly across regions and years. Further research involving multiple locations and seasons is essential to confirm the consistency and broader applicability of these findings.

Conclusions

This study demonstrated the promising potential of botanical extracts as sustainable alternatives to synthetic insecticides for managing *Euscelis* sp. infestations in *Ocimum basilicum*, while preserving the vital pollinator *A. mellifera*. The aqueous extracts from *Carica papaya*, *Azadirachta indica*, and *Calotropis procera* effectively reduced pest populations and enhanced seed yield, highlighting their dual benefit in pest control and pollinator safety. Notably, *C. papaya* extract significantly boosted seed production during the rainy season, while *A. indica* and *Ca. procera* showed stronger effects during the dry season, reflecting their adaptability to varying environmental conditions.
Additionally, *C. papaya* and *Ca. procera* treatments increased *A. mellifera* foraging activity without adverse effects, unlike the synthetic insecticide, which appeared to be repellent. These findings support the integration of botanical extracts into eco-friendly pest management strategies that align with pollinator conservation goals and improved agricultural productivity.
However, a key limitation of this study is that it was conducted at a single site and over only one rainy and one dry season. Further research involving multiple locations and seasons is essential to confirm the consistency and broader applicability of these findings. Future studies should also investigate the specific bioactive compounds responsible for these effects and assess their long-term impact on both pests and pollinators under real farming conditions.

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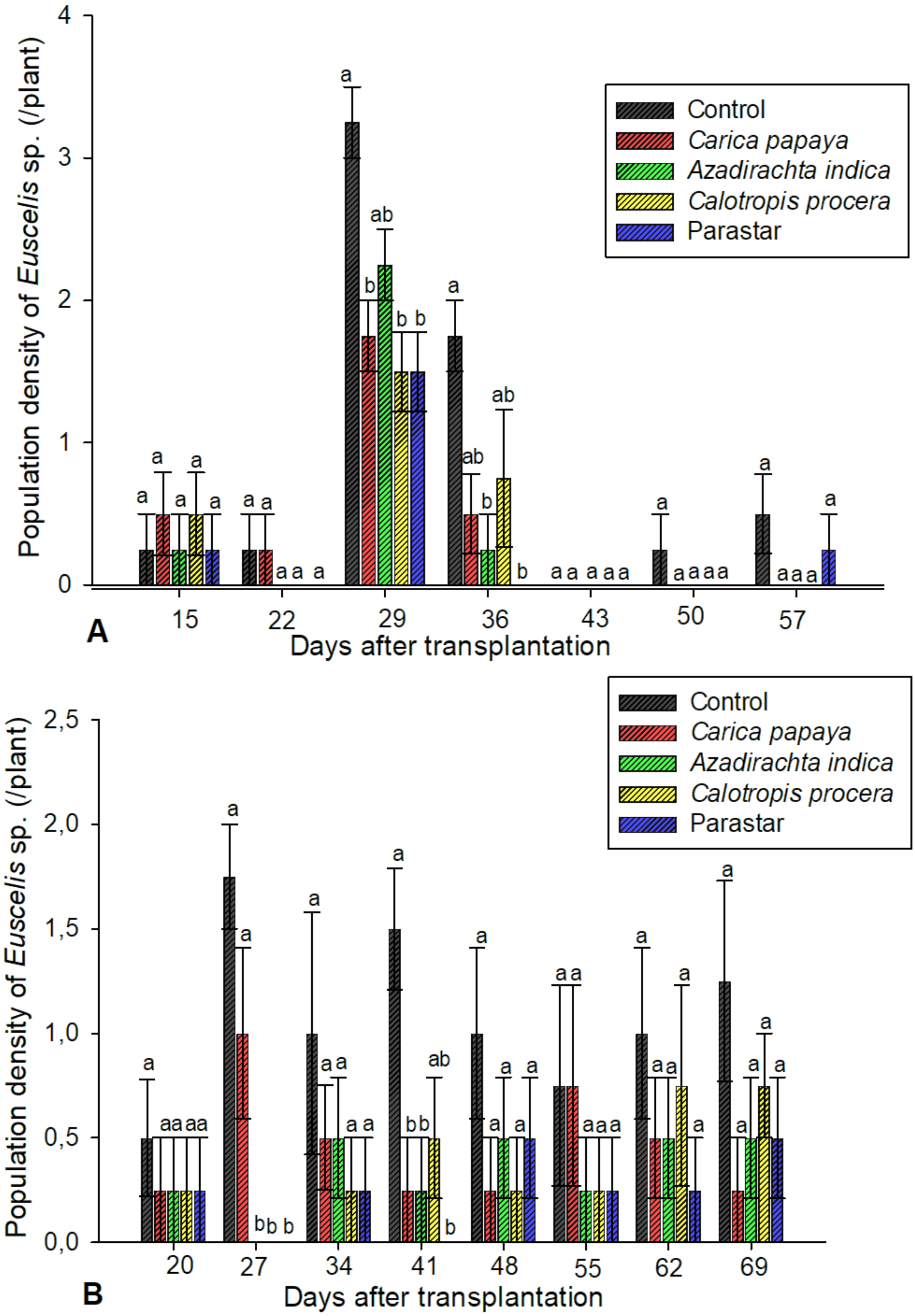

Figure 1. Population dynamic of Euscelis sp. on treated basil with botanical extracts during the rainy (A) and dry (B) seasons (means followed by the same letters are not significantly different with each other)

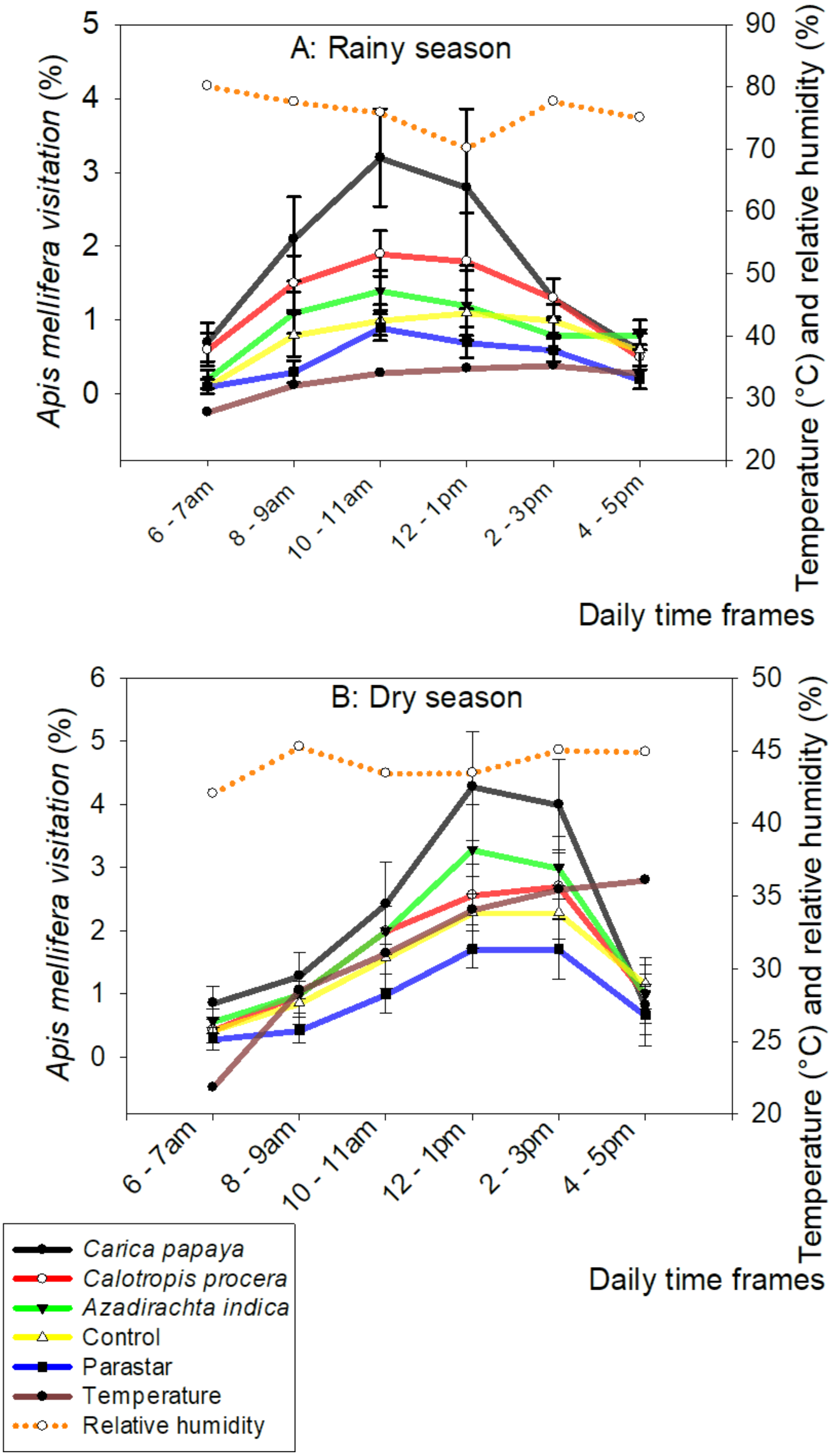

Figure 2. Honey bee visitation to basil flowers: temporal and insecticide-related effects during rainy (A) and dry (B) Seasons

Table 1. Diversity of insect pests recorded on *Ocimum basilicum*

Order	Family	Genus, Species	Rainy season		Dry season		Total	
			n	*p*	*n*	*p*	*n*	*P*
Coleoptera	Bostrichidae	*Apate monachus* (l)	17	3.42	-	-	17	1.91
	Chrysomelidae	*Mesoplatys cincta* (st, l)	15	2.01	20	5.10	35	3.93
	Coccinellidae	*Cheilomenes* sp. (l)	21	4.22	-	-	21	2.36
		Harmonia axyridis (l)	16	3.21	15	3.82	31	3.48
	Curculionidae	*Anthonomus* sp. (l)	20	4.02	22	5.61	42	4.72
Hemiptera	Aleyrodidae	*Bemisia* sp. (st, l)	27	5.42	32	8.16	59	6.66
	Cicadellidae	*Euscelis* sp. (st, l)	**91**	**18.73**	**80**	**20.40**	**171**	**19.23**
	Pentatomidae	(1 sp.) (l)	22	4.42	15	3.82	37	4.16
	Pyrrhocoridae	*Dysdercus delauneyi* (l)	14	2.81	60	15.30	74	8.32
		Dystercus sp. (fl, l)	23	4.62	35	8.92	58	6.65
Lepidoptera	Noctuidae	*Mamestra* sp. (l)	23	4.62	25	6.37	48	5.39
		(1 sp.1) (l)	13	2.61	-	-	13	1.46
		(1 sp.2) (st, l)	11	2.20	-	-	11	1.23
		(1 sp.3) (l)	20	4.02	-	-	20	2.24
	Sphingidae	*Agrius* sp. (st, l)	19	3.83	25	6.37	44	4.94
Orthoptera	Gryllacrididae	*Borneogryllacris* sp. (l)	65	11.06	-	-	65	7.31
	Tettigoniidae	*Neoconocephalus* sp. (fl, l)	28	5.63	63	16.07	91	10.23

	(1 sp.) (l)	52	10.46	-	-	52	5.84
Total	**18 species**	**497**	**100**	**392**	**100**	**889**	**100**

n: number of visits on leaves, flowers and stems of basil; *p*: percentage of visits associated with each insect species; $\chi 2 = 0.62$; df = 1; $p > 0.05$; l: leaves, fl: flowers, st: stems; sp.: unidentified species

Table 2. Diversity and abundance of insect pollinators collecting pollen and/or nectar on *Ocimum basilicum* flowers during rainy and dry seasons

Order	Family	Genus and Species	Rainy season		Dry season		Total	
			n	*p*	*n*	*p*	*n*	*P*
Diptera	Muscidae	*Musca domestica* (ne)	0	-	50	6.72	50	4.30
	Syrphidae	(1sp.) (ne)	0	-	25	3.36	25	2.15
Hymenoptera	Apidae	*Amegilla atrocincta* (ne, po)	0	-	36	4.83	36	3.10
		***Apis mellifera* (ne, po)**	**312**	**74.82**	**375**	**50.40**	**687**	**59.34**
		Lipotrich escollaris (po)	0	-	25	3.36	25	2.15
		Xylocopa olivacea (ne, po)	0	-	36	4.83	36	3.10
		Xylocopa inconstans (ne)	0	-	36	4.83	36	3.10
	Megachilidae	*Megachile* sp. (ne)	0	-	96	12.90	96	8.26
Lepidoptera	Nymphalidae	*Acrea acerata* (ne)	56	13.42	20	2.68	76	6.54
		Hypolimnas misippus (ne)	21	5.03	25	3.36	46	3.96
	Pieridae	*Mylothris chloris* (ne)	28	6.71	20	2.68	48	4.13
Total		**11 species**	**417**	**100**	**744**	**100**	**1161**	**100**

n: number of visits; *p* = percentage of visits; ne: collection of nectar; po: collection of pollen; sp.: unidentified species

Table 3. Mean duration of a bee visit for nectar or pollen harvesting from the flowers of *Ocimum basilicum* treated with aqueous botanical extracts

Treatment	Rainy season		Dry season	
	Nectar	Pollen	Nectar	Pollen
	mean ± se	mean ± se	mean ± se	mean ± se
Carica papaya	10.52 ± 0.63^{a}	4.67 ± 0.43^{a}	12.52 ± 0.59^{a}	5.66 ± 0.43^{a}
Calotropis procera	9.02 ± 0.64^{a}	4.32 ± 0.28^{a}	9.45 ± 0.45^{a}	5.32 ± 0.28^{a}
Azadirachta indica	8.02 ± 0.35^{a}	4.14 ± 0.25^{a}	8.35 ± 0.35^{a}	4.95 ± 0.25^{a}
Control	5.90 ± 0.37^{b}	3.70 ± 0.28^{b}	6.80 ± 0.37^{b}	3.70 ± 0.28^{b}
Parastar	4.90 ± 0.35^{b}	3.00 ± 0.30^{b}	5.90 ± 0.333^{b}	3.00 ± 0.30^{b}
$F_{(4,168)}$	18.93^{***}	3.28^{*}	3.47^{***}	3.08^{*}

*: $p < 0.05 > 0.01$; ***: $p < 0.001$

Values in the same column followed by the same letter are not significantly different according to Turkey test at 5% level

Table 4. Mean abundance of foragers per 1000 flowers of treated *Ocimum basilicum* with botanical extracts

Treatment	Rainy season	Dry season
	mean ± se	mean ± se
Carica papaya	4.67 ± 0.43	22.35 ± 1.75^{a}
Calotropis procera	4.32 ± 0.28	18.46 ± 1.28^{a}
Azadirachta indica	3.74 ± 0.25	16.51 ± 1.02^{b}
Control	3.70 ± 0.28	15.80 ± 1.02^{b}
Parastar	3.00 ± 0.30	13.24 ± 0.82^{b}
$F_{(4,168)}$	1.74^{ns}	5.90^{***}

ns: not significant; ***: $p < 0.001$

Values in the same column followed by the same letter are not significantly different according to Turkey test at 5% level

Table 5. Mean foraging speed of *Apis mellifera* on *Ocimum basilicum* flowers treated with botanical extracts during the rainy and dry seasons.

Treatment	Rainy season	Dry season	*T-value*	p
	mean ± se	mean ± se		
Carica papaya	13.54 ± 1.16^{a}	17.28 ± 1.06^{a}	2,38	0.043
Calotropis procera	11.08 ± 0.78^{ab}	15.58 ± 1.09^{ab}	3.36	0.001
Azadirachta indica	13.90 ± 3.03^{a}	17.37 ± 1.55^{a}	1.13	0.115
Control	8.89 ± 0.63^{b}	13.25 ± 1.00^{ab}	3,68	0.000
Parastar	11.71 ± 0.97^{ab}	12.63 ± 1.33^{b}	0.56	0.622
$F_{(4,102)}$	2.62^{*}	3.43^{***}		

*: p < 0.05 > 0.01; ***: p < 0.001

Values in the same column followed by the same letter are not significantly different according to Turkey test at 5% level

Table 6. Fructification rate (%) and normal seed percent of *Ocimum basilicum* treated with botanical extracts under different pollination regimes

Treatment	Rainy season		Dry season	
	Fructification rate	Normal seeds	Fructification rate	Normal seeds
Group 1: non protected flowers				
Control	98.64 ± 0.38^{ab}	95.89 ± 1.20^{ab}	98.64 ± 0.38^{b}	95.89 ± 1.21^{b}
C. papaya	99.40 ± 0.00^{ab}	98.91 ± 0.19^{ab}	99.40 ± 0.32^{ab}	98.87 ± 0.19^{a}
A. indica	99.58 ± 0.20^{a}	98.83 ± 0.40^{ab}	99.77 ± 0.16^{a}	98.74 ± 0.40^{a}
C. procera	98.37 ± 0.39^{b}	95.24 ± 1.81^{b}	99.65 ± 0.22^{ab}	98.77 ± 0.41^{a}
Parastar	99.60 ± 0.00^{a}	99.47 ± 0.24^{a}	99.48 ± 0.26^{ab}	98.91 ± 0.27^{a}
$F_{4,115}$	4.70^{**}	3.82^{**}	2.55^{*}	4.58^{**}
Group 2: protected flowers				
Control	84.05 ± 2.60^{ab}	93.40 ± 2.20	83.45 ± 2.52	93.40 ± 2.20
C. papaya	86.70 ± 0.82^{a}	93.76 ± 2.33	82.75 ± 2.12	92.89 ± 2.37
A. indica	78.50 ± 1.55^{bc}	93.46 ± 2.74	76.62 ± 2.63	93.46 ± 2.74
C. procera	77.66 ± 1.46^{c}	93.52 ± 2.14	80.90 ± 1.77	94.73 ± 2.48
Parastar	80.74 ± 0.98^{abc}	94.64 ± 1.89	80.24 ± 2.04	92.29 ± 2.62
$F_{4,115}$	5.60^{***}	0.07^{ns}	1.43^{ns}	0.13^{ns}
Group 3: protected flowers and open for exclusive visit of *Apis mellifera*				
Control	100.00 ± 0.00^{a}	98.57 ± 0.45	100.00 ± 0.00	98.57 ± 0.45
C. papaya	99.89 ± 0.11^{ab}	99.33 ± 0.25	99.31 ± 0.69	98.66 ± 0.36
A. indica	99.73 ± 0.19^{ab}	97.15 ± 1.21	100.00 ± 0.00	97.36 ± 1.22
C. procera	99.03 ± 0.48^{b}	99.03 ± 0.32	99.32 ± 0.31	99.17 ± 0.30
Parastar	99.86 ± 0.10^{ab}	98.83 ± 0.31	99.55 ± 0.32	98.54 ± 0.40
$F_{4,115}$	2.61^{*}	1.93^{ns}	0.90^{ns}	1.07^{ns}
Group 4: protected flowers and open during 10 minutes without any visit				
Control	91.53 ± 1.16	91.80 ± 3.34	91.53 ± 1.16^{a}	91.80 ± 3.35
C. papaya	89.07 ± 1.00	88.70 ± 4.12	83.56 ± 1.87^{bc}	88.23 ± 4.22
A. indica	90.496 ± 0.61	94.04 ± 2.07	91.10 ± 0.58^{ab}	92.33 ± 3.43
C. procera	91.16 ± 0.64	98.49 ± 0.32	78.21 ± 2.85^{c}	98.88 ± 0.26
Parastar	91.49 ± 0.515	96.65 ± 1.44	88.78 ± 1.45^{ab}	95.59 ± 2.12
$F_{4,115}$	1.55^{ns}	2.17^{ns}	10.47^{***}	1.80^{ns}

ns (not significant): $p > 0.05$; *: $p < 0.05$; **: $p < 0.01 > 0.001$; ***: $p < 0.001$

Means in a column followed by the same letter(s) do not differ significantly at the 5% level by Tukey test

Table 7. Modes of reproduction in *Ocimum basilicum* and fructification rate as contribution of combined impacts of pollinators and plant extracts (TFr) as well as of *Apis mellifera* exclusively (AmFr)

Treatment	Parameter (mean ± SE)							
	Rainy season				Dry season			
	TFr	AmFr	TC	TA	TFr	AmFr	TC	TA
Control	7.7 ± 1.3^{c}	8.5 ± 1.2^{c}	15.3 ± 2.7^{b}	84.7 ± 2.7	8.1 ± 0.9	10.0 ± 0.6^{ab}	17.5 ± 2.4^{ab}	82.5 ± 2.4^{ab}
C. papaya	15.6 ± 1.5^{ab}	15.7 ± 2.1^{ab}	16.8 ± 2.1^{ab}	83.2 ± 2.1	10.4 ± 0.8	10.8 ± 1.0^{a}	12.8 ± 0.8^{b}	87.2 ± 0.8^{a}
A. indica	10.1 ± 0.5^{bc}	8.9 ± 0.6^{bc}	23.2 ± 2.6^{a}	76.8 ± 2.6	10.3 ± 0.7	9.2 ± 0.7^{ab}	21.2 ± 1.5^{a}	78.8 ± 1.5^{b}
C. procera	20.0 ± 2.2^{a}	21.1 ± 2.9^{a}	18.8 ± 1.8^{ab}	81.2 ± 1.8	8.4 ± 0.9	7.9 ± 0.8^{b}	21.1 ± 1.4^{a}	78.9 ± 1.4^{b}
Parastar	11.6 ± 1.3^{bc}	10.8 ± 1.5^{bc}	19.4 ± 2.0^{ab}	80.6 ± 2.0	9.1 ± 0.5	8.4 ± 0.5^{ab}	19.0 ± 0.9^{a}	81.0 ± 0.9^{ab}
$F_{4,115}$	11.05***	8.52***	3.48**	1.77^{ns}	1.79^{ns}	2.61*	8.01***	5.20***

TFr: combined impacts of pollinators and treatment on the fruiting rate; AmFr: impact of *Apis mellifera* on the fruiting rate; TC: outcrossing rate; TA: self-pollination in the broad sense

ns (not significant): $p > 0.05$; *: $p < 0.05$; **: $p < 0.01 > 0.001$; ***: $p < 0.001$

Means in a column followed by the same letter(s) do not differ significantly at the 5% level by Tukey test

Table 8. Seed yield (kg/ha) of *Ocimum basilicum* treated with botanical extracts during the rainy and dry season

Treatment	Season (mean ± SE)		*T-value*	p
	Rainy	Dry		
Control	18.94 ± 0.63^{c}	20.76 ± 0.29^{c}	1.15	0.329
Carica papaya	21.55 ± 0.96^{ab}	23.71 ± 0.20^{a}	2.20	0.108
Azadirachta indica	21.54 ± 0.43^{ab}	23.34 ± 0.33^{ab}	3.35	0.015
Calotropis procera	20.27 ± 0.37^{ab}	21.86 ± 0.29^{bc}	3.38	0.015
Parastar	22.42 ± 0.67^{a}	21.99 ± 0.55^{bc}	0.49^{ns}	0.641
$F_{4,15}$	4.65^{**}	11.65^{***}		

**: $p < 0.01 > 0.001$; ***: $p < 0.001$

Means in a column followed by the same letter(s) do not differ significantly at the 5% level by Tukey test