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Research Article

Keywords: Apis mellifera, Watermelon, yield, north Cameroon

Posted Date: November 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10713696/v1

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Additional Declarations: No competing interests reported.

Contribution of *Apis mellifera* (Hymenoptera: Apidae) to the Pollination and Yield on *Citrullus lanatus* (Cucurbitaceae) in Bockle and Pitoa, North Cameroon

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Abstract

Insect pollination is a key determinant of cucurbit productivity, yet little information is available on the role of *Apis mellifera* in watermelon production in northern Cameroon. This study was conducted in Bocklé (2023) and Pitoa (2025) to assess the contribution of *A. mellifera* to the pollination and yield of *Citrullus lanatus*. Investigations focused on the composition of the flower-visiting insect community, foraging behaviour, floral resources collected, bee abundance, and the effects of bee visits on crop reproductive performance. A total of 1195 floral visits belonging to eight insect species were recorded, of which 67.19% were performed by *A. mellifera*, the dominant floral visitor at both sites. Worker bees collected mainly nectar (61.08% of visits) and, to a lesser extent, pollen (38.91%), with peak foraging activity occurring between 08 : 00 and 10 : 00 h. Flowers visited by insects, particularly those exclusively visited by *A. mellifera*, exhibited significantly higher fruit set, seed number per fruit, and percentage of normal seeds than insect-excluded flowers. The contribution of *A. mellifera* to fruit set reached 83.33% across both experimental seasons, while its contribution to seed production and normal seed percentage was estimated at 23.96% and 86.43%, respectively. These findings demonstrate that *A. mellifera* is the principal pollinator of *C. lanatus* in Bockle and Pitoa. Establishing managed honeybee colonies near watermelon fields and adopting pollinator-friendly farming practices could represent effective agroecological strategies for sustainably improving watermelon production while conserving pollination ecosystem services.

Keywords: *Apis mellifera;* Watermelon; yield; north Cameroon.

Introduction

Food insecurity remains one of the greatest challenges facing humanity (FAO et al. 2019). Despite substantial progress in agricultural production, more than 735 million people were still suffering from hunger in 2023, particularly in developing countries where rapid population growth, climate change, and ecosystem degradation continue to undermine food systems (FAO et al. 2024). In sub-Saharan Africa, this situation is particularly alarming because of low agricultural productivity and the heavy dependence of rural populations on food and vegetable crops (FAO et al. 2024). In Cameroon, sustainably increasing crop productivity has become a national priority to meet the growing food demand while preserving natural resources.

Among the biological factors influencing crop productivity, insect-mediated pollination is one of the most important ecosystem services. Approximately 75% of the world's leading food crops benefit from animal pollination, mainly by insects, while nearly 35% of global agricultural production directly depends on this ecological service (Klein et al. 2007 ; IPBES 2016). Efficient pollination not only increases fruit set but also improves fruit quality, fruit weight, size, seed production, and market value (Garibaldi et al. 2013 ; Potts et al. 2016). The global economic value of pollination services is estimated at several hundred billion US dollars annually.

Among insect pollinators, *Apis mellifera* L. (Hymenoptera: Apidae) is considered one of the most important species for agriculture. Its foraging behavior, floral constancy, abundance, and ease of management make it a highly efficient pollinator of numerous fruit, oilseed, and vegetable crops (Free 1993 ; Delaplane & Mayer 2000 ; Abrol 2012). Floral visits by this honey bee promote pollen transfer between male and female flowers, thereby enhancing fertilization, fruit set, seed development, and crop yields. However, pollinator populations are currently experiencing alarming declines due to agricultural intensification, habitat fragmentation, climate change, and excessive pesticide use (Potts et al. 2010; IPBES 2016). This decline represents a major threat to global food security.

Watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai) is one of the major vegetable crops belonging to the family Cucurbitaceae. It is cultivated in more than 100 countries for its fruits, which are rich in water, natural sugars, vitamins (A, C, and B), lycopene, and antioxidant compounds that provide important health benefits. Global watermelon production currently exceeds 100 million tons per year, making it one of the most widely consumed fruits worldwide (FAOSTAT 2024). In Africa, and particularly in Cameroon, watermelon cultivation constitutes an important source of income for smallholder farmers and contributes significantly to food and nutritional security.

Like most cucurbits, *C. lanatus* is a monoecious species bearing separate male and female flowers on the same plant. Pollination is primarily carried out by insects, with bees serving as the principal pollen vectors. Female flowers generally require several hundred viable pollen grains to produce well-developed, marketable fruits (Free 1993). Insufficient pollination results in poor fruit set, malformed fruits, reduced seed numbers, lower fruit weight, and consequently significant yield losses.

Numerous studies conducted in Europe, America, Asia, and Africa have demonstrated that bees significantly enhance the production of cucurbit crops, including watermelon, melon, cucumber, and squash (Delaplane & Mayer 2000 ; Garibaldi et al. 2013 ; Abrol 2012). In Cameroon, several studies have also highlighted the importance of flower-visiting insects in the pollination of economically important crops (Pando et al. 2013 ; Adamou & Tchuenguem 2014 ; Kengni et al. 2015 ; Dounia & Tchuenguem 2016 ; Djakbé et al. 2017 ; Diguir et al. 2020 ; Kingha et al. 2020 ; Adamou et al. 2020 ; Kingha et al. 2021). These studies demonstrated that pollinators significantly increase fruit set, fruit weight, seed production, and crop yields. Nevertheless, most of these investigations have focused on other crops and different agroecological zones.

In Northern Cameroon, watermelon cultivation has expanded considerably owing to its high economic profitability and increasing market demand. The locality of Pitoa represents one of the major vegetable-producing areas in the region. Despite its economic importance, little scientific information is available regarding the interactions between *A. mellifera* and the flowers of *C. lanatus* under the agroecological conditions of this area. Furthermore, the composition of flower-visiting insect communities, foraging activity, and pollination efficiency may vary considerably according to climatic conditions, agricultural practices, and landscape characteristics (Winfree et al. 2011). This lack of information limits the development of integrated management strategies combining pollinator conservation, beekeeping, and sustainable crop production.

We hypothesized that floral visits by *A. mellifera* significantly improve pollination, fruit set, fruit characteristics, and the yield of *C. lanatus* under the agroecological conditions of Bocklé and Pitoa.

Therefore, the present study aimed to evaluate the contribution of *A. mellifera* to the pollination and yield of *C. lanatus* in Bocklé and Pitoa (Northern Cameroon). Specifically, the objectives were to: (i) inventory the flower-visiting insect fauna associated with watermelon in Bocklé and Pitoa; (ii) characterize the foraging activity of *A. mellifera* on *C. lanatus* flowers;

(iii) assess its pollination efficiency and (iv) quantify its effects on fruit set, fruit characteristics, seed production, and crop yield.

Materials and methods

Study Area

Field experiments were conducted from January to April 2023 (dry season) in Bocklé (9°17′29.81″ N, 13°25′4.39″ E; altitude: 169 m above sea level) and from February to May 2025 (dry season) in Pitoa (9°25′22.51″ N, 13°20′1.22″ E; altitude: 160 m above sea level), located in the Garoua III and Pitoa Subdivisions, respectively, Benoue Division, North Region, Cameroon.

The North Region of Cameroon lies between 8° and 10° N latitude and 12° and 16° E longitude (PCD 2011). It belongs to the Sudano-Sahelian agroecological zone, covering approximately 65,576 km² with a population exceeding 1,227,000 inhabitants (PCD 2011). The climate is characterized by two distinct seasons: a short rainy season lasting five months (May to September) and a long dry season extending over seven months (October to April). The average annual rainfall is approximately 1,000 mm (PCD 2011). Mean annual temperatures range from 25.5 to 32.5 °C, while relative humidity varies between 42% and 83%. Annual rainfall ranges from 750 to 1,250 mm, and annual sunshine duration varies from 1,291 to 2,082 h.

The region is characterized by an extensive plain interspersed with numerous swampy and seasonally flooded areas (PCD 2011). The soils are predominantly ferruginous, developed on crystalline basement rocks and sandstone formations (PCD 2011). They are generally deep, sandy-textured soils with good agricultural potential, including fertile alluvial soils occurring along the Benoue River floodplain (PCD 2011). The hydrographic network mainly consists of the River and several seasonal streams (locally known as *mayos*), which flow during the rainy season and frequently overflow, causing flooding (PCD 2011).

The natural vegetation is mainly composed of wooded savanna interspersed with gallery forests along watercourses. The dominant plant species include *Hyparrhenia rufa*, *Borassus aethiopum*, *Boswellia dalzielii*, *Commiphora africana*, *Lannea microcarpa*, *Bombax costatum*, *Prosopis africana*, *Vitellaria paradoxa*, as well as plantations of *Azadirachta indica* and *Eucalyptus camaldulensis*. The herbaceous layer is dominated by several grass species, including *Andropogon gayanus*, *Cymbopogon giganteus*, and *Loudetia* spp. The African fan palm (*Borassus aethiopum*) is particularly abundant in swampy and seasonally flooded areas (PCD 2011).

Biological Materials

The plant material consisted of seeds of watermelon (F1 Kolos s variety) obtained from SEMAGRI in Garoua. With the exception of the honey bee *Apis mellifera*, the animal material consisted of all insect species naturally present in the experimental site's environment that visited the flowers of *C. lanatus*.

Experimental Plot Establishment, Sowing, and Crop Management

From January to April 2023 and from February to May 2025, an experimental plot covering 437 m² was established. The site was cleared, fenced, ploughed, and divided into eight subplots, each measuring 8 m × 4.5 m, separated by 1-m-wide alleys (Farda & Tchuenguem, 2018). The entire experimental field was surrounded by a 1-m-wide border alley.

Seeds of *C. lanatus* were sown in six rows per subplot, with three seeds placed in each planting hole. Plant spacing was 50 cm within rows and 75 cm between rows, following the protocol of Farda and Tchuenguem (2018). From seed germination until the appearance of the first flower, weeds were controlled every two weeks using a hand hoe. During the flowering and fruit maturation stages, weeding was carried out manually to avoid disturbing pollinator activity (Azo'o et al. 2010).

Determination of the Reproductive Mode of *Citrullus lanatus*

During the flowering periods of watermelon in 2023 and 2025, a total of 240 flower buds were tagged each year on 15 plants per subplot. Two treatments were established, each consisting of 120 flowers : (i) 120 tagged flowers left unprotected and freely accessible to insect visitors (Treatment 1 in 2023 and Treatment 3 in 2025), and (ii) 120 tagged flowers protected from insect visits using gauze bags with a mesh size of 1 mm² (Treatment 2 in 2023 and Treatment 4 in 2025). At harvest, the number of fruits produced in each treatment was recorded, and the fruiting index (FI) was calculated using the following formula:

$$\mathbf{FI = Fa / Fb}$$

where **Fa** is the number of fruits formed and **Fb** is the initial number of viable flowers borne by the plants (Tchuenguem et al. 2001).

For each experimental year, the difference between the fruiting indices of the two treatments was used to estimate the rates of cross-pollination (CP) and self-pollination (SP) according to the equations proposed by Demarly (1977):

$$\mathbf{C_P\ (\%) = [(F_{IX} - F_{IY}) / F_{IX}] \times 100}$$

where **FIX** and **FIY** are the fruiting indices of the open-pollinated and insect-excluded treatments, respectively.

$$\mathbf{SP\ (\%) = 100 - CP}$$



Figure 1. *Citrullus lanatus* plant bearing a tagged flower left open to natural pollination (a) and a tagged flower protected from insect visits using a gauze bag (b).

Study of the Foraging Activity of *Apis mellifera* on *Citrullus lanatus* Flowers

Determination of the Visitation Frequency of *Apis mellifera*

During both experimental years, observations were conducted daily from 28 February to 20 March 2023 and from 25 March to 22 April 2025**,** following six daily observation periods : 06:00–07:00, 08:00–09:00, 10:00–11:00, 12:00–13:00, 14:00–15:00, and 16:00–17:00**.** Observations were carried out on the flowers assigned to Treatments A and E. During each observation period, four successive inspections (at 15-minute intervals) were performed on every open, unprotected flower. At each inspection, the number of visits (Nx) made by *A. mellifera* was counted and recorded. The visitation frequency (Fxh) of *A. mellifera* during each observation period was calculated using the following equation (Tchuenguem, 2001):

$$\mathbf{Fxh\ (\%) = (Nx / Nt) \times 100}$$

Where Nt represents the total number of visits recorded throughout the entire observation period.

During each experimental year, the number of newly opened flowers of *C. lanatus* was counted every morning before the beginning of observations and throughout the flowering period. The visitation frequencies of *A. mellifera* were subsequently correlated with the number of open flowers to determine the foraging pattern of this honey bee.

Floral Resources Collected

The floral resources collected by *A. mellifera* workers were recorded during the same observation periods used to determine visitation duration. A bee inserting its proboscis into the

floral corolla was considered to be collecting nectar, whereas a bee scraping the anthers with its mandibles and legs was regarded as collecting pollen (Jean-Prost 1987).

Abundance of Foragers

The maximum number of *A. mellifera* workers simultaneously foraging on a single flower and per 1,000 flowers was recorded during the same periods used for the visitation frequency assessment, following six daily observation intervals (07:00–08:00, 09:00–10:00, 11:00–12:00, 13:00–14:00, 15:00–16:00, and 17:00–18:00) (Tchuenguem, 2001).

Direct counts were used to determine the abundance of foragers per flower. The abundance per 1,000 flowers (**A1000**) was estimated by counting the number of honey bee workers on a known number of open flowers using the following equation (Tchuenguem, 2005):

$$\mathbf{A1000 = (Ax / Fx) \times 1000}$$

*Where **Fx** = number of open flowers and **Ax** = number of* A. mellifera *workers counted on the flowers at observation time* x.

Duration of Floral Visits

Using a digital stopwatch and during the same observation periods as those used for estimating forager abundance, the duration of each floral visit for nectar and pollen collection was recorded separately.

The stopwatch was started as soon as an *A. mellifera* worker landed on a *C. lanatus* flower and stopped when the bee left the flower for another plant species. Simultaneously, the number of flowers visited was recorded (Tchuenguem, 2005).

Whenever a forager returned to a previously visited *C. lanatus* flower, this event was considered a new visit. Any interrupted visit was also recorded together with the cause of interruption to assess the influence of other flower-visiting organisms on the foraging activity of *A. mellifera* (Tchuenguem, 2005).

The foraging speed (**Fs**), expressed as the number of flowers visited per minute, was calculated according to Jacob-Remacle (1989) using the following equation:

$$\mathbf{Fs = (Fx / dx) \times 60}$$

where: dx = duration of the visit (s) and Fx = number of flowers visited during the recorded time interval.

Influence of Selected External Factors

The number of times *A. mellifera* workers switched from *C. lanatus* flowers to flowers of other plant species, and vice versa, during a single foraging trip was recorded through direct observations (Tchuenguem 2005). Samples of each visited plant species were collected, and voucher specimens were prepared for botanical identification.

Ambient temperature and relative humidity at the study site were recorded every 30 minutes throughout each observation day using a thermo-hygrometer (Tchuenguem, 2001). These climatic variables were subsequently used to assess their influence on the foraging activity of *A. mellifera*.

Assessment of the Contribution of *Apis mellifera* to the Production of *Citrullus lanatus*

In February 2023 and March 2025, a total of 300 flower buds were tagged, and two experimental treatments were established during each study year.

- Treatment 5 (2023) or Treatment 7 (2025) (Kingha et al. 2021): This treatment consisted of 200 insect-protected flowers intended to receive a single visit from *Apis mellifera*. As soon as each flower opened, the gauze bag was carefully removed during the period of peak foraging activity of *A. mellifera* workers (between 08:00 and 09:00 h). The unprotected flower was then observed for 1 to 10 min to record a possible visit by the honey bee. Immediately after a single visit by *A. mellifera*, the flower was re-bagged and was no longer manipulated.
- Treatment 6 (2023) or Treatment 8 (2025) (Diguir, 2020): This treatment consisted of 100 insect-protected flowers used as a control. Upon flower opening, the gauze bag was carefully removed between 08:00 and 09:00 h, and the flower was monitored for 1 to 10 min while preventing visits by *A. mellifera* or any other flower visitor. After this observation period, the flower was immediately re-bagged and received no further manipulation.

For each experimental year, after fruit development in Treatments C (or G) and D (or H), the fruit set attributable to *A. mellifera* (**Pt**) was calculated according to Djackbé (2017) using the following equation:

$$[Pt (\%) = \frac{FC - FD}{FC} \times 100]$$

Where and F_C = fruit set obtained from flowers that were bagged, uncovered, received a single visit by *Apis mellifera*, and then re-bagged and F_D = fruit set obtained from flowers that were bagged, uncovered, not visited by any insect, and subsequently re-bagged (Tchuenguem, 2001).

Data Analysis

The collected data were subjected to descriptive statistical analyses, including the calculation of means, standard deviations, and percentages. Four statistical tests were

performed: (a) One-way Analysis of Variance (ANOVA) to compare the means of more than two groups; (b) Student's t-test to compare the means of two independent groups; (c) Chi-square (χ^2) test to compare percentages or proportions; (d) Pearson's correlation coefficient (r) to examine the linear relationships between quantitative variables.

All statistical analyses were performed using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA) and IBM SPSS Statistics software. Statistical significance was assessed at the 5% probability level ($P < 0.05$).

Results

Mode of reproduction of *Citrullus lanatus*

The fruiting indices were 0.92, 0.75, 0.70, and 0.00 for treatments A, B, E, and F during the 2023 and 2025 growing seasons, respectively. Accordingly, in 2023, the cross-pollination rate (CP) and self-pollination rate (SP) were 18.48% and 81.52%, respectively, whereas in 2025 they reached 100% and 0%, respectively. For the two seasons combined, the cumulative CP and SP rates were 59.24% and 40.76%, respectively.

These results indicate that *C. lanatus* exhibits a mixed breeding system combining self-pollination and cross-pollination, with a predominance of cross-pollination.

Importance of *Apis mellifera* within the Flower-Visiting Insect Community of *Citrullus lanatus*

During the two experimental seasons, a total of 1.195 floral visits were recorded on *C. lanatus* flowers (table 1). These visits were distributed among eight species belonging to two orders (Hymenoptera and Lepidoptera) and four families. Hymenoptera was by far the dominant order, accounting for more than 98% of all flower-visiting insects recorded, whereas Lepidoptera were poorly represented. *A. mellifera* was the most abundant flower visitor during both study years, with 803 visits, representing 67.19% of all recorded visits. Its relative abundance was markedly higher in Pitoa (85.28%) than in Bocklé (59.17%). This high visitation frequency indicates a strong attractiveness of *A. mellifera* to *C. lanatus* flowers and suggests that it is the principal potential pollinator of this crop in both study sites.

In Bocklé, the most abundant species after *A. mellifera* were *Amegilla* sp. 1 (25.48%) and *Xylocopa olivacea* (13.28%), two solitary bee species well known for their high pollination efficiency. In contrast, the flower-visiting community in Pitoa was less diverse, with only a few species accompanying *A. mellifera*, namely *Amegilla* sp., *Megachile frontalis*, *Macronomia vulpinia*, and *Tarucus balkanicus*, each representing less than 7% of the recorded visits. Lepidopteran species (*Acraea acerata*, *Tarucus balkanicus*, and *Eurema* sp.) accounted for less

than 3% of the total floral visits, suggesting that they play only a minor role in watermelon pollination compared with bees.

The marked dominance of *A. mellifera* demonstrates that this species is particularly attracted to watermelon flowers. This preference may be explained by several factors, including abundant nectar secretion, high pollen availability, synchronized mass flowering, and a floral morphology that is readily accessible to honey bees.

The considerably higher visitation frequency observed in Pitoa (85.28%) than in Bocklé (59.17%) suggests that environmental conditions in Pitoa were more favorable for the foraging activity of *A. mellifera*. This difference may be associated with a higher density of honey bee colonies, lower competition from alternative floral resources, more favorable microclimatic conditions, and differences in agricultural landscape structure.

Overall, the results demonstrate that *A. mellifera* is the predominant flower visitor of *C. lanatus* in both Bocklé and Pitoa. This dominance confirms that the western honey bee is the principal pollinator of this cucurbit crop under the agroecological conditions of Northern Cameroon.

Table 1. Number and percentage of floral visits by different insect species recorded on *Citrullus lanatus* flowers at Bocklé (2023) and Pitoa (2025).

Order	**Family**	**Genus, Species, floral products**	**Bocklé 2023**		**Pitoa 2025**		**Total**	
			n_1	**P_1 (%)**	**n_2**	**P_2 (%)**	**n_t**	**P_t (%)**
Hymenoptera	Apidae	*Apis mellifera* (Nectar, Pollen)	490	59.17	313	85.28	803	67.19
		Amegilla sp. 1 (Nectar, Pollen)	211	25,48	-	-	211	17.65
		Megachile frontalis (Nectar)	-	-	23	6.26	23	1.92
		Xylocopa olivacea (Nectar, Pollen)	110	13.28	-	-	110	9.20
		Macronomia vulpinia (Nectar, Pollen)	-	-	22	5.99	22	1.84
Lepidoptera	Nymphalidae	*Acraea acerata* (Nectar)	10	1.20	-	-	10	0.83
	Lycaenidae	*Tarucus balkanicus* (Nectar)	-	-	9	2.45	9	0.75
	Pieridae	*Eurema* sp. (Nectar)	7	0.84	-	-	7	0.58
Total (02 order : 04 family)		**08 species**	**828**	**100**	**367**	**100**	**1195**	**100**

Visitation Rhythm of *Apis mellifera* on *Citrullus lanatus* Flowers

The visitation curves showed that the foraging activity of *A. mellifera* on *C. lanatus* flowers followed a well-defined daily pattern. The number of visits increased progressively after flower opening, reached a peak during the morning (8:00 – 9:00 a.m.), and then gradually declined throughout the afternoon. This pattern, consistently observed at both Boklé and Pitoa,

indicates a strong synchronization between the foraging behavior of honeybee workers and the floral phenology of *C. lanatus*.

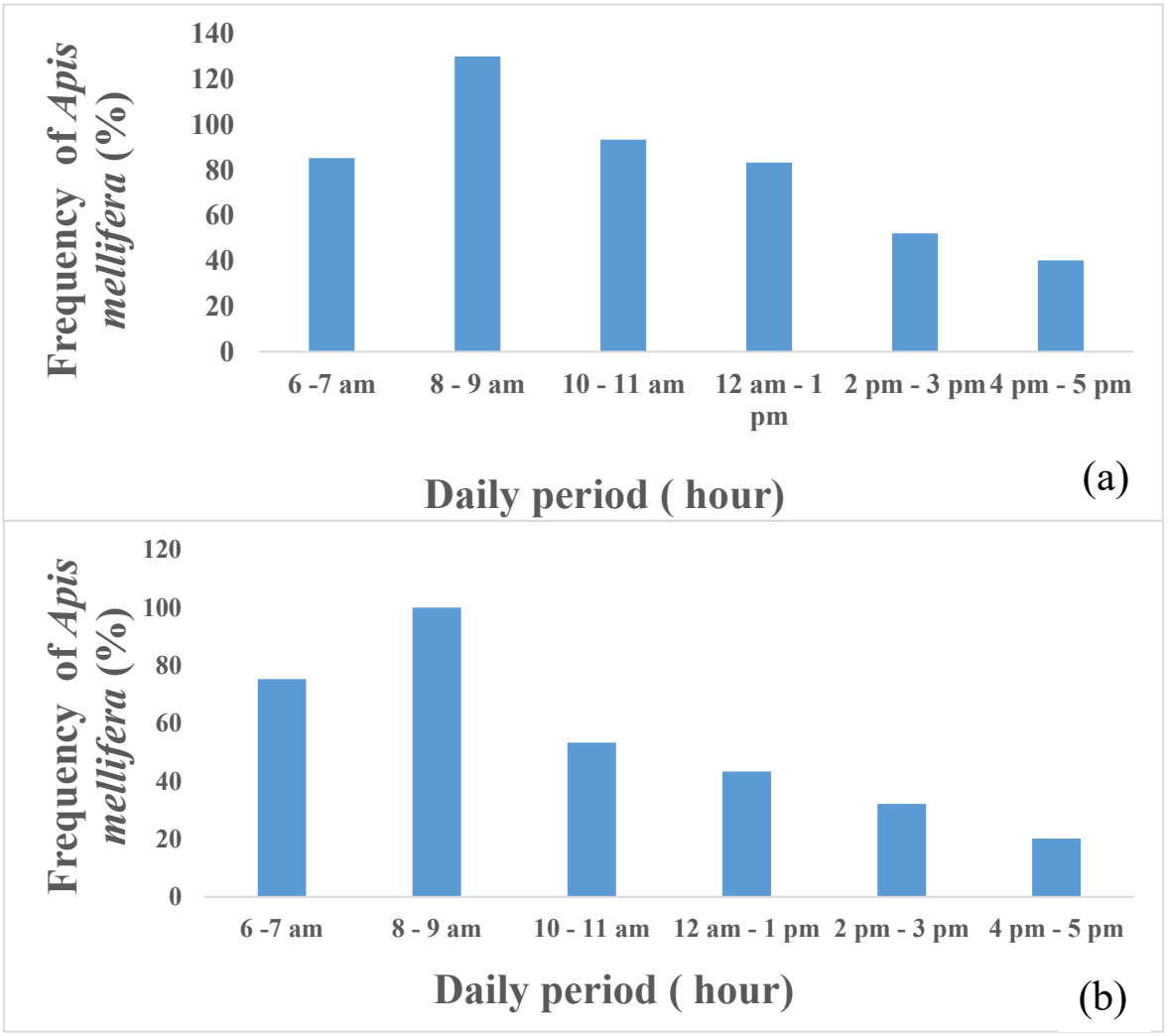


Figure 2. Frequency of *Apis mellifera* visits to *Citrullus lanatus* flowers during different daily time intervals at Boklé in 2023 (a) and Pitoa in 2025 (b).

Floral Resources Collected

On both male and female flowers of *C. lanatus*, *A. mellifera* workers collected predominantly nectar and, to a lesser extent, pollen. Across the two years of observation, of the 1,195 recorded floral visits, 61.08% were devoted to nectar collection, whereas 38.91% were associated with pollen collection (Figure 3).



Figure 3. *Apis mellifera* workers collecting pollen (A) and nectar (B) from a *Citrullus lanatus* flower in 2023.

Abundance of *Apis mellifera* Foragers on *Citrullus lanatus* Flowers

The highest mean number of *A. mellifera* workers per flower was one individual in both 2023 and 2025. The mean abundance of foragers per 1000 *C. lanatus* flowers (A1000) was 915 (n = 160; SD = 129.28) in 2023 and 800 (n = 83; SD = 119.98) in 2025. The difference between these two means was significant ($t = 0.21$; $df = 140$; $P < 0.05$). Across both years, the cumulative mean abundance was 857.5 (n = 155.5; SD = 118.75). The high abundance recorded per 1,000 flowers is likely attributable to the availability and attractiveness of *C. lanatus* nectar to *A. mellifera*, as well as to the abundance of honey bee colonies in the vicinity of the experimental site.

Duration of Visits per Flower

The mean duration of a visit by *A. mellifera* to male and female *C. lanatus* flowers for nectar and pollen collection was 7.60 s (n = 950; SD = 5.42) and 4.60 s (n = 656; SD = 0.45), respectively, in 2023, and 8.84 s (n = 957; SD = 8.14) and 5.20 s (n = 857; SD = 11.58), respectively, in 2025. Across both years, the overall mean duration of a visit was 8.22 s for nectar collection and 4.90 s for pollen collection.

The average visit duration was longer during nectar collection than during pollen collection. This difference is expected because nectar extraction requires bees to reach the nectaries located at the base of the corolla, whereas pollen collection mainly involves brushing the anthers.

Foraging Speed

A. mellifera workers visited an average of 9.44 flowers per minute (n = 39; SD = 0.63) in 2023 and 22.53 flowers per minute (n = 83; SD = 25.70) in 2025. The difference between

these two means was highly significant ($t = 8.18$; $df = 154$; $P < 0.01$). Across both years, the overall foraging speed averaged 8.95 flowers per minute.

Influence of External Factors

Effect of Fauna

During both observation periods, *A. mellifera* workers were interrupted in their foraging activity by other flower visitors competing for nectar. In 2023, of the 828 recorded visits, 300 (36.23%) were interrupted. Among these, 218 (72.66%) were disrupted by other *A. mellifera* workers, whereas the remaining 82 (27.33%) were interrupted by *Amegilla* sp. In 2025, of the 367 recorded visits, 167 (45.50%) were interrupted, including 100 (59.88%) by *A. mellifera* workers and 67 (40.11%) by *Megachile frontalis*.

Effect of Surrounding Flora

During both years of the study, *A. mellifera* workers also visited flowers of several plant species growing near the experimental plots to collect nectar and/or pollen. These included *Vigna unguiculata* (Fabaceae: nectar and pollen), *Allium cepa* (Amaryllidaceae: nectar and pollen), *Mangifera indica* (Anacardiaceae: nectar), and *Zea mays* (Poaceae: pollen). However, no movement of *A. mellifera* workers from *C. lanatus* flowers to flowers of other plant species, or vice versa, was observed in either 2023 or 2025.

Beekeeping Value of *Citrullus lanatus*

During the flowering period of *C. lanatus*, *A. mellifera* workers actively collected both nectar and pollen from the flowers. These observations demonstrate the strong attractiveness of the floral resources of *C. lanatus* to honey bees and indicate that this species can be classified as a highly nectariferous and moderately polliniferous bee plant.

Contribution of *Apis mellifera* to the Pollination of *Citrullus lanatus*

Field observations showed that *A. mellifera* workers regularly came into contact with the anthers and subsequently with the stigmas of female flowers while collecting nectar, thereby promoting the transfer of compatible pollen. This behavior confirms the important role of honey bees as efficient pollinators of *C. lanatus*, in agreement with the findings of Free (1993) and Klein et al. (2007).

Although active pollen collection was not always observed, successive movements between male and female flowers enable efficient passive transport of pollen grains adhering to the hairs on the thorax and legs. Several recent studies have demonstrated that honey bee pollination significantly improves fruit set, fruit weight, fruit diameter, seed number, the

proportion of well-developed seeds, and overall market quality of watermelon fruits (Bomfim et al. 2023 ; Layek et al. 2021).

These findings further support the use of managed *A. mellifera* colonies as an effective agroecological strategy to optimize watermelon production while ensuring the conservation of pollination ecosystem services. The results obtained showed that treatments allowing insect visitation, particularly by *A. mellifera*, exhibited the highest reproductive performance of *C. lanatus*. Open flowers (OF) and flowers exclusively visited by *A. mellifera* (HVF) recorded high fruit set rates, whereas flowers protected from insect visitation (PF) showed no fruit set at Pitoa (2025) and a significantly reduced fruit set at Bocklé (2023). These findings clearly demonstrate that insect-mediated pollination is essential for successful watermelon fruit production.

The complete absence of fruit set in protected flowers at Pitoa confirms that *C. lanatus* relies heavily on insect pollinators to transfer pollen from male to female flowers. This dependence is a well-established characteristic of Cucurbitaceae, whose reproductive system requires pollen transport by insects to achieve effective fertilization (Free 1993; Klein et al. 2007). The few fruits obtained from protected flowers at Bocklé may have resulted from accidental self-pollination or minor pollen contamination during experimental manipulations, a phenomenon previously reported in studies on insect-pollinated crops (Delaplane & Mayer 2000).

Flowers visited exclusively by *A. mellifera* exhibited fruit set rates (80.0% at Bocklé and 74.41% at Pitoa) (table 2) that were very similar to those recorded for open flowers (84.16% and 76.0%, respectively). This close similarity indicates that the honey bee alone provides a substantial proportion of the pollination service required by *C. lanatus*. The high pollination efficiency of this species can be attributed to its foraging behavior, characterized by strong floral constancy, repeated movements between male and female flowers, and frequent contact with both anthers and stigmas during nectar collection. According to Grüter and Ratnieks (2011), such flower constancy minimizes pollen loss between plant species and substantially increases the transfer of compatible pollen.

Fruit quality parameters followed the same trend. Treatments exposed to insect pollination consistently produced higher numbers of seeds and greater percentages of normal seeds. At Bocklé, open flowers produced 93.41% normal seeds compared with only 76.52% in protected flowers that remained inaccessible to insect visitors. Likewise, at Pitoa, flowers visited exclusively by *A. mellifera* produced 92.40% normal seeds.

Table 2. Fruit set, mean number of seeds per fruit, mean fruit diameter, mean fruit length, mean fruit weight, and percentage of normal seeds obtained under each *Citrullus lanatus* treatment at Bocklé in 2023 and at Pitoa in 2025.

Site/Years	Treatments	NFE	NFF	TF (%)	Seeds/ fruits			NTG	NGN	%GN
					N	M	S			
Bocklé 2023	T1(F1)	120	101	84,16	9315	119,43	39,50	9315	8702	93,41
	T2 (Fp)	120	90	75	7316	133,40	29,60	7316	6010	82,14
	T5 (Fva)	200	130	80	8545	122,25	15,18	8545	7686	89,94
	T6 (Fps)	100	70	70	6547	102,15	19,64	6547	5010	76,52
Pitoa 2025	T3 (F1)	60	46	76	6256	104,26	58,30	6256	5602	89,54
	T4 (Fp)	60	0	0	0	0	0	0	0	0
	T7 (Fva)	43	32	74,41	57,52	133,76	78,04	5752	5315	92,40
	T8 (Fps)	33	0	0	0	0	0	0	0	0

Fl: open flowers; **Fp:** protected flowers; **Fva:** flowers visited exclusively by *Apis mellifera*; **Fps:** protected flowers uncovered but receiving no insect visits; **NFE:** number of flowers examined; **NFF:** number of fruits formed; **NGN:** number of normal seeds; **NTG:** total number of seeds; **TF:** fruit set; **% GN:** percentage of normal seeds.

Contribution of *Apis mellifera* to the Improvement of *Citrullus lanatus* Yield

The results obtained demonstrate that *A. mellifera* makes a substantial contribution to improving the reproductive performance of *C. lanatus*. The fruit set attributable to this honey bee was estimated at **66.67%** in Bocklé (2023), **100%** in Pitoa (2025), and **83.33%** across both experimental sites. Likewise, the mean number of seeds per fruit attributable to *A. mellifera* reached **19.71%** in Bocklé, **28.20%** in Pitoa, and **23.96%** when both study sites were combined. The percentage of normal seeds attributable to *A. mellifera* was **72.86%** in Bocklé, **100%** in Pitoa, and **86.43%** across the two experimental sites.

Flowers visited exclusively by *A. mellifera* consistently exhibited superior reproductive performance compared with flowers that were initially bagged, subsequently exposed, and then re-bagged without receiving any insect visit. In Bocklé, flowers visited by *A. mellifera* achieved a fruit set of **80%**, compared with **70%** in unvisited flowers, whereas the percentage of normal seeds increased from **76.52%** to **89.94%** following honey bee visitation. In Pitoa, no fruit set was recorded on flowers that remained unvisited by insects, whereas flowers visited exclusively by *A. mellifera* exhibited a fruit set of **74.41%** and a normal seed percentage of **92.40%**. These findings clearly demonstrate that the absence of insect pollinators markedly reduces, or even completely suppresses, fruit production, whereas a single visit by *A. mellifera* is sufficient to ensure effective fertilization.

Discussion

Mode of Reproduction of *Citrullus lanatus*

The present results indicate that *C. lanatus* exhibits a mixed breeding system combining self-pollination and cross-pollination, with a clear predominance of cross-pollination. This reproductive strategy ensures reproductive success when pollinator activity is limited while maximizing genetic diversity and reproductive performance under abundant insect visitation, thereby enhancing the ecological adaptability of the species.

These findings are consistent with those of the French Variety and Seed Study and Control Group (GEVES 2011), which described *C. lanatus* as a predominantly cross-pollinated species that can nevertheless be improved using breeding approaches commonly applied to self-pollinated crops. Similarly, Ma et al. (2022) and Rader et al. (2023) emphasized that insect pollinators substantially improve fruit set, seed production, and fruit quality in Cucurbitaceae despite the species retaining a limited capacity for self-fertilization.

The predominance of cross-pollination is closely linked to the floral biology of *C. lanatus*, which bears separate male and female flowers and therefore depends largely on insects for pollen transfer. The short daily flowering period reported by Azo'o et al. (2010) further limits the pollination window, making efficient pollinators essential for successful fertilization. The differences observed between the 2023 and 2025 cropping seasons suggest that environmental conditions, particularly pollinator abundance, climatic factors, and floral resource availability, influence the relative contribution of self- and cross-pollination. The absence of fruit set in protected flowers at Pitoa and the very limited fruit production in protected flowers at Boklé indicate that although self-pollination is biologically possible, it contributes only marginally under field conditions, whereas insect-mediated cross-pollination remains the principal mechanism ensuring effective fertilization and optimal fruit production.
Overall, these findings confirm the pivotal role of insect pollinators in the reproductive biology of *C. lanatus* and highlight the importance of pollinator-friendly agricultural practices, including minimizing insecticide applications during flowering, conserving natural and semi-natural habitats, and strategically placing managed honey bee colonies near watermelon fields to maximize pollination services and crop productivity.

Importance of *Apis mellifera* within the Flower-Visiting Insect Community of *Citrullus lanatus*

The predominance of *A. mellifera* among the floral visitors recorded in the present study demonstrates its central role within the pollinator community of *C. lanatus* under the

agroecological conditions of northern Cameroon. Its high visitation frequency indicates not only a strong attraction to watermelon flowers but also a high potential for effective pollen transfer between male and female flowers, thereby enhancing pollination success and crop productivity.

These observations are in agreement with those of Delgado-Carrillo et al. (2024), who identified *A. mellifera* as the dominant pollinator of watermelon flowers and reported that the majority of effective pollen transfers were performed by this species. Their study further demonstrated that the high visitation rate of honey bees significantly increased fruit set and improved fruit quality. Similar conclusions were reached by Tonola et al. (2026) in Tanzania, where watermelon fields visited by *A. mellifera* produced significantly higher yields than fields from which bee visitation was excluded. According to these authors, honey bee pollination increased watermelon yield by nearly 90%, highlighting the considerable agronomic value of managed honey bee colonies.

The dominance of *A. mellifera* can be explained by several behavioural characteristics that make this species one of the most efficient crop pollinators. Honey bees exhibit strong floral constancy, allowing individual foragers to visit successive flowers of the same plant species during a single foraging trip, thereby maximizing the transfer of compatible pollen. In addition, the waggle dance enables efficient recruitment of nestmates to profitable floral resources, resulting in a rapid increase in the number of foragers exploiting flowering watermelon fields (Abrol 2012). These behavioural adaptations greatly enhance pollination efficiency, particularly in crops such as *C. lanatus*, where successful fruit production depends largely on repeated pollen transfer between male and female flowers.

Although *A. mellifera* represented the dominant floral visitor, other bee genera, including *Amegilla*, *Xylocopa*, and *Megachile*, were also observed visiting watermelon flowers. Their presence indicates that pollination of *C. lanatus* is supported by a diverse pollinator assemblage in which managed and wild bees may provide complementary pollination services. Nicholson et al. (2024) and Campbell et al. (2023) similarly reported that wild bees make substantial contributions to cucurbit pollination, particularly when their activity complements that of honey bees, thereby improving both pollination stability and crop productivity.

The particularly high abundance of *A. mellifera* recorded at Pitoa compared with Boklé probably reflects local ecological conditions that favour honey bee foraging. Differences in the density of managed or wild colonies, the availability of alternative flowering plants, landscape composition, and climatic conditions during the flowering period may all influence honey bee abundance in agricultural fields. Kennedy et al. (2023) demonstrated that landscapes

characterized by abundant floral resources and attractive flowering crops promote honey bee activity and significantly enhance crop pollination services.

In contrast, Lepidopteran visitors accounted for only a small proportion of the flower-visiting insects recorded during the study. Their limited abundance suggests that they contribute only marginally to the pollination of *C. lanatus*. This observation is consistent with Delgado-Carrillo et al. (2024), who concluded that bees remain the most efficient pollinators of cucurbit crops because of their active pollen-collecting behaviour, repeated movements between flowers, and frequent contact with both anthers and stigmas during foraging.

Taken together, these findings clearly demonstrate that *A. mellifera* constitutes the principal pollinator within the flower-visiting insect community of *C. lanatus* in northern Cameroon. While the presence of wild bees may reinforce pollination through complementary ecological functions, the exceptionally high abundance and foraging efficiency of honey bees strongly support their strategic importance for sustainable watermelon production and justify the integration of managed colonies into pollinator-friendly agricultural systems.

Activity of *Apis mellifera* on *Citrullus lanatus* Flowers

The daily foraging pattern of *A. mellifera* observed in the present study closely reflects the flowering biology of *C. lanatus*. Honey bee activity reached its maximum during the early morning, corresponding to the period when watermelon flowers are most attractive. At this stage, anthers release large quantities of viable pollen, stigmas are fully receptive, and nectar secretion generally reaches its highest level, thereby creating optimal conditions for intensive bee visitation. As the day progresses, increasing air temperature, declining relative humidity, and the gradual depletion of floral rewards reduce flower attractiveness, resulting in a progressive decline in visitation frequency during the afternoon.

This temporal pattern is consistent with recent studies identifying microclimatic conditions as the principal drivers of honey bee foraging behaviour. Requier et al. (2022) demonstrated that temperature and relative humidity directly regulate foraging intensity, whereas Potts et al. (2023) emphasized that pollination efficiency depends largely on the synchronization between pollinator activity and the period of maximum floral receptivity. Similarly, Khalifa et al. (2021) reported that entomophilous crops derive the greatest pollination benefits from morning honey bee visits, when floral resources are at their maximum availability.

The predominance of morning foraging observed in the present study also agrees with previous investigations conducted on Cucurbitaceae. Numerous studies have shown that most *A. mellifera* visits occur before midday, a period during which pollen transfer between male

and female flowers is maximized. Efficient pollen deposition on receptive stigmas increases ovule fertilization and ultimately enhances fruit set, seed number, fruit weight, and commercial fruit quality. In this regard, Garibaldi et al. (2021) demonstrated that pollinator abundance and activity directly determine the productivity of insect-pollinated crops, while Kleijn et al. (2023) highlighted the importance of bee diversity and visitation intensity in sustaining high agricultural yields.

The remarkably similar daily visitation patterns recorded at Boklé and Pitoa suggest that the foraging rhythm of *A. mellifera* is primarily governed by the floral phenology of *C. lanatus* rather than by local ecological differences. Nevertheless, the higher visitation intensity observed at one site compared with the other may reflect differences in colony density, landscape composition, the availability of competing floral resources, or prevailing climatic conditions. These factors are known to influence the abundance of foraging honey bees without substantially modifying their characteristic daily activity rhythm.

The temporal distribution of foraging activity was closely associated with the type of floral resources collected. Nectar constituted the principal resource harvested by worker bees throughout the flowering period, whereas pollen collection represented a smaller proportion of visits. This predominance of nectar foraging is consistent with the floral biology of Cucurbitaceae, whose flowers generally produce abundant quantities of sugar-rich nectar that are highly attractive to honey bees (Nicolson 2022). Nectar provides the carbohydrates required to sustain the energetic demands of adult workers, whereas pollen supplies proteins and lipids essential for brood development (Brodschneider & Crailsheim 2010).

The persistence of nectar collection throughout the day further suggests that watermelon flowers maintain nectar secretion over an extended period, although the quantity and accessibility of this resource gradually decline during the afternoon. Similar foraging patterns have been described for *A. mellifera* on melon and cucumber flowers, where nectar availability strongly influences visitation frequency (Pashte et al. 2021 ; Requier et al. 2022). According to Hung et al. (2018), both the quantity and quality of floral rewards are major determinants of honey bee foraging preferences and visitation dynamics.

The relatively high abundance of honey bee workers recorded on watermelon flowers confirms the strong attractiveness of *C. lanatus* to *Apis mellifera*. This attractiveness is largely determined by floral density, nectar production, and sugar concentration, all of which stimulate the recruitment of nestmates through the waggle dance (Seeley 2019). The significant difference observed between the two study years probably reflects interannual climatic variation affecting both nectar secretion and honey bee flight activity. Temperature, relative

humidity, and rainfall are known to influence floral resource availability and the intensity of pollinator activity (Klein et al. 2023). Comparable levels of honey bee abundance have been reported in several tropical entomophilous crops, where *A. mellifera* frequently represents more than 70% of all flower visitors (Willmer 2011 ; Dolezal et al. 2019).

The duration of individual flower visits observed during this study is consistent with previous reports on bee–flower interactions in cucurbit crops. Visit duration depends primarily on nectar availability, nectar viscosity, floral morphology, and the intensity of competition among flower visitors (Artz & Nault 2021 ; Rader et al. 2020). Longer visits generally increase pollen deposition on receptive stigmas and consequently improve pollination efficiency (Ollerton 2021).

Likewise, the significant differences in foraging speed recorded between the two study years indicate that the efficiency of floral exploitation is strongly influenced by environmental conditions. Increased foraging speed may result either from high floral density, which facilitates rapid movement between flowers, or from reduced nectar availability, requiring workers to visit a greater number of flowers to satisfy their energetic needs (Seeley 2019). Giannini et al. (2020) further demonstrated that temperature, solar radiation, and relative humidity directly influence the foraging performance of honey bees. Under favourable conditions, increased movement among flowers may also enhance the frequency of pollen transfer events, thereby promoting cross-pollination in entomophilous crops.

Interactions observed between *A. mellifera* and other flower-visiting insects illustrate the exploitative competition commonly occurring when several pollinator species simultaneously exploit limited floral resources. Such interactions may reduce the time spent on individual flowers while increasing the total number of flowers visited during a foraging trip, thereby indirectly enhancing pollen movement within the crop. Brittain et al. (2018) and Garibaldi et al. (2021) similarly demonstrated that pollinator diversity often improves the complementarity and stability of pollination services despite the occurrence of interspecific competition.

Finally, the marked floral fidelity exhibited by *A. mellifera* confirms the characteristic flower constancy behaviour of this species. Honey bees generally continue visiting flowers of the same plant species during a single foraging trip, thereby maximizing energetic efficiency and improving learning of floral traits (Grüter & Ratnieks 2011). Such behaviour substantially increases compatible pollen transfer between conspecific flowers and is particularly advantageous for crops such as *C. lanatus*, whose reproductive success largely depends on

efficient cross-pollination (Ollerton 2021). Similar patterns have recently been reported by Requier et al. (2022) in Mediterranean entomophilous crops.

Collectively, these findings demonstrate that the foraging behaviour of *A. mellifera* is highly synchronized with the flowering biology of *C. lanatus*. This synchronization maximizes pollen transfer, enhances pollination efficiency, and reinforces the ecological and agronomic importance of honey bees for sustainable watermelon production. Moreover, the abundant nectar and pollen resources provided by watermelon flowers suggest that *C. lanatus* may also represent an important forage crop for apiculture, allowing its cultivation near apiaries to simultaneously improve crop pollination and support honey bee colony development.

Contribution of *Apis mellifera* to the Pollination of *Citrullus lanatus*

The daily foraging pattern of *A. mellifera* observed in the present study closely reflects the flowering biology of *C. lanatus*. Honey bee activity peaked during the early morning, when watermelon flowers are most attractive because anthers release abundant viable pollen, stigmas are fully receptive, and nectar secretion reaches its maximum. As the day progresses, increasing temperature, declining relative humidity, and the depletion of floral rewards reduce flower attractiveness and consequently decrease visitation frequency.

This pattern is consistent with studies showing that microclimatic conditions are the principal drivers of honey bee foraging behaviour. Requier et al. (2022) demonstrated that temperature and relative humidity regulate foraging intensity, whereas Potts et al. (2023) highlighted the importance of synchrony between pollinator activity and floral receptivity. Likewise, Khalifa et al. (2021) reported that entomophilous crops benefit most from morning honey bee visits, when floral resources are most abundant.

The predominance of morning foraging agrees with previous studies on Cucurbitaceae, where most *A. mellifera* visits occur before midday, maximizing pollen transfer between male and female flowers. Efficient pollen deposition enhances ovule fertilization, fruit set, seed production, fruit weight, and commercial quality. Similarly, Garibaldi et al. (2021) showed that pollinator abundance directly influences crop productivity, while Kleijn et al. (2023) emphasized the importance of bee diversity and visitation intensity for maintaining high yields. The similar visitation patterns observed at Boklé and Pitoa indicate that the foraging rhythm of *A. mellifera* is mainly governed by the floral phenology of *C. lanatus*, although differences in visitation intensity may reflect variation in colony density, landscape composition, floral resource availability, or climatic conditions.

Nectar was the principal floral resource collected by worker bees, whereas pollen represented a smaller proportion of visits. This predominance of nectar collection is consistent

with the abundant sugar-rich nectar produced by Cucurbitaceae flowers (Nicolson 2022). Nectar supplies the carbohydrates required by adult workers, whereas pollen provides proteins and lipids essential for brood development (Brodschneider & Crailsheim 2010). The persistence of nectar collection throughout the day further suggests prolonged nectar secretion, as also reported for melon and cucumber (Pashte et al. 2021; Requier et al. 2022). Hung et al. (2018) likewise identified the quantity and quality of floral rewards as major determinants of honey bee foraging preferences.

The relatively high abundance of honey bee workers confirms the strong attractiveness of *C. lanatus*, which is largely determined by floral density, nectar production, and sugar concentration stimulating recruitment through the waggle dance (Seeley 2019). Interannual differences probably reflect climatic variation affecting nectar secretion and flight activity (Klein et al. 2023). Similar levels of abundance have been reported for tropical entomophilous crops, where *A. mellifera* often represents more than 70% of flower visitors (Willmer 2011; Dolezal et al. 2019).

The duration of flower visits agrees with previous reports indicating that visit duration depends on nectar availability, nectar viscosity, floral morphology, and competition among flower visitors (Artz & Nault 2021; Rader et al. 2020). Longer visits generally increase pollen deposition and improve pollination efficiency (Ollerton 2021). Likewise, differences in foraging speed between study years indicate a strong influence of environmental conditions. High floral density or reduced nectar availability may increase movement between flowers (Seeley 2019), while temperature, solar radiation, and relative humidity also affect foraging performance (Giannini et al. 2020).

Interactions between *A. mellifera* and other flower visitors illustrate exploitative competition for limited floral resources. Although such interactions may shorten individual visits, they can increase the total number of flowers visited, thereby enhancing pollen transfer. Similar conclusions were reported by Brittain et al. (2018) and Garibaldi et al. (2021), who showed that pollinator diversity improves the complementarity of pollination services despite interspecific competition.

Finally, the strong floral fidelity exhibited by *A. mellifera* confirms its characteristic flower constancy behaviour (Grüter & Ratnieks 2011), which promotes compatible pollen transfer among conspecific flowers and is particularly advantageous for crops such as *C. lanatus* that depend on efficient cross-pollination (Ollerton 2021). Comparable observations were reported by Requier et al. (2022).

Overall, these findings demonstrate that the foraging behaviour of *A. mellifera* is highly synchronized with the flowering biology of *C. lanatus*. This synchronization maximizes pollen transfer and pollination efficiency, reinforcing the ecological and agronomic importance of honey bees for sustainable watermelon production. Moreover, the abundant nectar and pollen resources provided by watermelon flowers indicate that *C. lanatus* also represents an important forage crop for apiculture, supporting both crop pollination and honey bee colony development.

Contribution of *Apis mellifera* to the Improvement of *Citrullus lanatus* Yield

The present study demonstrates that the remarkable improvement in the yield of *C. lanatus* is directly associated with the pollination services provided by *A. mellifera*. During nectar and pollen collection, worker bees repeatedly contacted the reproductive organs of male and female flowers, ensuring efficient transfer of compatible pollen. Their frequent movements among flowers enhanced both geitonogamous and, more importantly, cross-pollination, thereby promoting complete ovule fertilization, improved fruit set, normal fruit development, and the production of well-developed seeds.

The superior reproductive and productive performances recorded in flowers accessible to honey bees indicate that efficient pollination is a major determinant of watermelon yield. Enhanced pollen deposition on receptive stigmas stimulates fertilization of a greater number of ovules, resulting in improved seed formation and the hormonal regulation required for optimal fruit growth. Consequently, the higher fruit set and greater proportion of normal seeds observed in the present study are direct consequences of the intensive pollination activity of *A. mellifera*, confirming the close relationship between pollination efficiency and crop productivity.

The differences observed between Boklé and Pitoa further suggest that the magnitude of the pollination benefit depends on local ecological conditions. Variations in honey bee colony abundance, floral resource availability, climatic conditions during flowering, and daily foraging intensity may influence the frequency of flower visitation and, consequently, the quantity of compatible pollen deposited on receptive stigmas. Despite these environmental differences, both experimental campaigns consistently demonstrated that *A. mellifera* remained the predominant flower visitor and the principal pollinator responsible for maximizing the reproductive success and yield of *C. lanatus*.

The present findings are fully consistent with current knowledge of watermelon pollination. Recent global syntheses have demonstrated that bees constitute the most abundant and effective floral visitors of *C. lanatus*, with *A. mellifera* ranking among the most efficient species in terms of pollen deposition, fruit set, seed production, and fruit quality. These studies further concluded that the introduction and appropriate management of honey bee colonies

represent one of the most effective agroecological strategies for sustainably increasing watermelon productivity.

Our results also corroborate the pioneering work of Free (1993), who highlighted the indispensable role of bees in the pollination of insect-dependent crops, as well as the global assessment of Klein et al. (2007), which identified Cucurbitaceae among the crop families showing a particularly high dependence on animal pollination. Similarly, Benachour and Louadi (2011) and Tuo et al. (2019) demonstrated that honey bees are exceptionally efficient pollinators because their repeated contact with floral reproductive organs maximizes compatible pollen transfer. The mechanisms described by Nzigidahera and Fofo (2010), particularly the repeated movement of pollinators between male and female flowers, adequately explain the high fruit set, normal seed development, and improved yield obtained in the present study.

The present results are further supported by previous studies conducted in Cameroon, which have highlighted the economic importance of *A. mellifera* for crop production. Adamou et al. (2020), working on *Bixa orellana*, and Farda et al. (2020), studying *Luffa cylindrica*, reported that honey bee visitation significantly increased fruit production, seed quality, and overall crop yield. The consistency between these studies and the present investigation confirms that the beneficial effects of honey bee pollination extend across a wide range of tropical entomophilous crops and reinforce the importance of conserving healthy pollinator populations in agricultural landscapes.

From an agroecological perspective, the integration of managed *A. mellifera* colonies into watermelon production systems represents an effective and environmentally sustainable management strategy. Beyond increasing fruit yield and seed quality, honey bee pollination contributes to greater production stability, enhances ecosystem services, supports biodiversity conservation, and simultaneously improves beekeeping productivity through increased nectar and pollen availability. Such a synergistic interaction between crop production and apiculture constitutes an important component of climate-smart and sustainable agricultural systems.

Overall, the present study provides compelling evidence that *A. mellifera* is the principal pollinator responsible for improving the reproductive performance and yield of *C. lanatus* under the agroecological conditions of northern Cameroon. Its high visitation frequency, floral constancy, and efficient pollen transfer substantially enhance fruit set, seed production, and overall crop productivity. These findings strongly support the adoption of pollinator-friendly agricultural practices, including the conservation of natural pollinator habitats and the strategic placement of managed honey bee colonies near watermelon fields, as practical approaches for

ensuring sustainable crop production while maintaining essential pollination ecosystem services.

Conclusion

This study demonstrates the pivotal role of *A. mellifera* in the pollination and yield improvement of *C. lanatus* under the agroecological conditions of northern Cameroon. Honeybees were the dominant floral visitors, accounting for more than two-thirds of all recorded visits, with foraging activity mainly directed toward nectar collection and peaking during the morning hours. Bee visitation significantly increased fruit set, seed number per fruit, and the proportion of normal seeds, confirming the high pollination efficiency of this species.

Overall, the results indicate that watermelon production strongly depends on insect-mediated pollination and that *A. mellifera* is the principal provider of this ecosystem service in the study area. The establishment of managed honeybee colonies near watermelon fields, together with reduced pesticide applications during flowering and the conservation of pollinator-friendly habitats, should be promoted as sustainable agroecological practices to enhance crop productivity while conserving pollinator biodiversity.

Future studies involving different watermelon cultivars, varying honeybee colony densities, and multiple agroecological zones are recommended to refine pollination management strategies and maximize watermelon production under tropical farming conditions.

Author contributions

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Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability No datasets were generated or analysed during the current study.

Declarations Competing interests. The authors declare no competing interests

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