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Foraging dynamics of honey bees (*Apis mellifera* L.) on sweet basil (*Ocimum basilicum* L.): relationships with colony performance and meteorological conditions

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Abstract

This study investigated the foraging dynamics of honey bees (*Apis mellifera* L.) on sweet basil (*Ocimum basilicum* L.) and their relationships with colony performance and meteorological conditions during the 2023 flowering season in Assiut, Upper Egypt. We monitored diurnal foraging activity (7 am - 3 pm) using quadrat counts and colony entrance observations. Colony performance metrics, bee population, sealed brood, pollen, and honey areas (sq. in²/colony), were assessed at 12-day intervals. Foraging peaked during 11 am - 1 pm in July (30-45 bee/min/colony) and declined sharply by September (<5-10 bee/min/colony). Colony performance peaked in late August, with significant increases in adult bee population (940 ± 183 sq. in²/colony; LMM: $P = 0.001$), sealed brood area (383 ± 34 sq. in²/colony; LMM: $P < 0.001$), and pollen stores (161 ± 34 sq. in²/colony; LMM: $P < 0.001$), followed by late-season declines. Honey stores increased steadily but showed no significant temporal change (LMM: $P = 0.298$). Air temperature correlated negatively with foraging activity ($P < 0.01$), with the strongest association at 11 am ($r = -0.636$). Wind speed negatively affected early-morning foraging ($r = -0.684^{**}$, $P < 0.01$). Relative humidity showed no significant effects. Hence, sweet basil serves as a critical late-summer forage source (critical dearth period) that supports colony buildup in the Assiut region, thereby enhancing colony performance and compensating for seasonal resource scarcity.

Keywords: *Ocimum basilicum* L., *Apis mellifera* L., Pollination, Foraging behavior, Colony performance, Climatic factors

INTRODUCTION

Sweet basil (*Ocimum basilicum* L.) is an important aromatic crop in Egypt that provides abundant nectar and pollen resources for honey bees (*Apis mellifera* L.) during the summer flowering period (Pereira et al. 2015, Egata 2021). In return, honey bees serve as the primary pollinator for this crop (Ilyasov et al., 2025, Oziegbe et al. 2016). In arid regions such as Upper Egypt, summer forage is often limited (Amro 2009), making basil a potentially valuable resource for supporting colony growth and preparing colonies for winter dearth.

Despite the agro-economic importance of basil–bee interactions (Fuentes-Polo et al. 2025), quantitative data on the foraging dynamics of *A. mellifera* on sweet basil, the resulting colony performance responses, and the mediating effects of local meteorological conditions remain limited in Upper Egyptian. Previous studies have focused mainly on honey quality (Hegazi et al. 2021) or general pollination (Kumar et al. 2024), but diurnal and seasonal foraging patterns, temporal changes in colony strength (adult bee population, sealed brood, pollen and honey stores), and the influence of air temperature, relative humidity, and wind speed have not been characterised in this region.

Meteorological conditions exert a decisive influence on honey bee foraging activity and colony productivity (Klein et al. 2019, Vincze et al. 2025). Air temperature, wind speed, and relative humidity directly affect flight energetics, thermoregulation, and resource detection (Abou-Shaara et al. 2017, Hennessy et al. 2020, Ngo et al. 2021). In arid regions such as Upper Egypt, summer temperatures frequently approach or exceed the thermal limits for sustained foraging, potentially constraining resource collection and colony growth (Stabentheine et al. 2021). Understanding how these climatic factors mediate bee visitation to basil is therefore essential for predicting colony performance under current and future environmental conditions.

To address these gaps, this study tested four hypotheses: (H1) foraging activity exhibits diurnal and seasonal variation, peaking within specific temperature windows; (H2) temperature, wind speed, and humidity significantly influence visitation rates, with moderate conditions promoting activity; (H3) colonies foraging on basil show measurable gains in brood area, food stores, and adult population; and (H4) meteorological effects on foraging are nonlinear, with optimal ranges beyond

which activity declines. Accordingly, we quantified diurnal and seasonal foraging patterns of *A. mellifera* on *O. basilicum*, assessed concurrent colony performance metrics, and elucidated the role of meteorological conditions in mediating bee–basil interactions in the Assiut region of Upper Egypt.

MATERIALS AND METHODS

Site description

The field experiment was conducted during the 2023 summer growing season at the research farm of the Bee Research Department, Plant Protection Research Institute, located in Abnobe, Assiut Governorate, Egypt (coordinates: 27° 15′ 7.2′′ N, 31° 7′ 24′′ E). The experimental plot was located 200 meters from the department's apiary, which housed 25 honey bee colonies. Site characterization confirmed a light clay soil profile and a moderate climate characterized by cold temperatures and low humidity. This location was chosen based on its history of uniform basil agricultural practices and its relative isolation from potential confounding factors, thereby providing a controlled environment conducive to obtaining reliable data.

Experimental design and field practices

A uniform 1.5-ha plot of the Genovese cultivar of *O. basilicum* was established within a larger basil cultivation area at the research farm. This plot was planted with the Genovese basil variety recommended by Muhammad (2017) to facilitate controlled monitoring and quantification of foraging bees on the flowering crop during the peak anthesis period (10 July till 25 September). Seeds were obtained from the Agricultural Research Center, Giza, Egypt, and sown manually on ridges at 60 cm × 30 cm spacing. Plants were thinned to one plant per hill 15 days after sowing. Standard conventional cultural practices were followed (Omer et al. 2008), and no insecticides, fungicides, or herbicides were applied during the flowering period. The basil plot provided a large, homogeneous foraging resource for the experimental colonies.

Honey Bee colonies

Twenty colonies of a local Carniolan hybrid (*Apis mellifera carnica* × *A. m. lamarkii*), each comprising eight frames covered with bees, were used in this study. Colonies were standardized for adult bee population, sealed brood area (approximately 250–300 sq. in²/colony), and queen age. All colonies were headed by young (<1-year-old), naturally mated sister queens to minimize genetic variation. Colonies were managed identically and positioned adjacent to the basil field with 3 m spacing between hives to ensure foraging independence.

Data Collection

Temporal Framework

The study was conducted over an 11-week period from July 10 to September 25, 2023, encompassing the complete flowering phenology of sweet basil in the Assiut region. A hierarchically structured data collection protocol was employed, comprising six sampling dates spaced at approximately 12-day intervals (July 10, July 25, August 9, August 24, September 8, and September 23), selected to systematically capture temporal progression throughout the flowering season. On each sampling date, observations were conducted at five fixed daily intervals (7 am, 9 am, 11 am, 1 pm, and 3 pm) to characterize diurnal foraging patterns, with five replicate measurements taken per colony at each time interval to account for within-interval variability.

Foraging activities

Foraging activity was assessed for 11 weeks (July 10–September 25, 2023) via weekly visual counts at all colony entrances. Metrics included counts of incoming and outgoing workers and incoming pollen foragers. Each weekly sampling day yielded five replicate measurements per colony. Data collection occurred at 2-hour intervals from 7 am to 3 pm daily. At each interval, a 10-minute observation period was used to count outgoing, incoming, and pollen-returning foragers at every colony entrance. These counts were averaged across colonies and intervals to derive a mean foraging rate (bee/min/colony). The magnitude of foraging activity observed provided a robust sample size for investigation, aligning with the approach of Nye and Mackensen (1970). Colonies were spatially separated by 3 m to ensure foraging independence. Quadrat sampling locations were spaced ≥10 m apart to minimize spatial autocorrelation. Statistical analyses incorporated the colony as a random intercept to account for repeated measures, thereby ensuring valid inference.

Diurnal temporal foraging dynamics of *A. mellifera*

To assess diurnal activity patterns, the foraging behavior of *A. mellifera* on our basil plot was monitored daily at five fixed intervals (7 am, 9 am, 11 am, 1 pm, and 3 pm) throughout the 2023 flowering season. Following the method of Amro (2021), a 1 m² wooden quadrat was used to count *A. mellifera* pollinators within a defined area over five-minute intervals per replicate. Bees were counted for 5 min within each 1 m² quadrat and converted to bees/m²/min. To minimize observer bias, all enumerators completed standardized training with inter-observer reliability exceeding 85% agreement prior to data collection. Observers were rotated systematically among sampling locations and were blinded to experimental hypotheses during counts. Calibration checks were performed biweekly to ensure sustained consistency.

Colony metrics

Standardized apicultural metrics adult bee population, sealed brood, and honey and pollen storage areas were used to quantify colony strength. Monitoring was conducted at 12-day intervals from July 10 to September 25, 2023 (six sampling

events), employing a gridded Hoffman frame (divided into squares) for measurement (Omar & Amro 2023). Following Jeffree (1958), sealed brood area was converted to an estimated number of worker cells using a standardized density of 26 cells per square inch (sq. in²/colony). The same approach was applied to estimate cell equivalents for stored honey and pollen areas. The adult bee population was estimated from the total number of frames completely covered (both sides) by bees, applying the established conversion of 2,000 adults per fully covered comb (Jeffree 1958). All colony evaluations were conducted before sunset to ensure the majority of foragers had returned.

Environmental measurements

Environmental measurements, including daily air temperature (°C), relative humidity (%), and wind speed (m/s), were obtained from local weather stations (Assiut Agricultural Research Station automated weather station) approximately 500 m from the experimental plot. These variables were then used to examine relationships with pollination services for basil and the performance of honey bee colonies. A relevant climatic feature was the complete absence of precipitation during the flowering interval at the study sites.

Statistical analysis

The data showed no significant departure from normality (Shapiro–Wilk test). All statistical analyses were performed in R version 4.1.2 (R Core Team 2021) using the packages lme4 and lmerTest, and in SPSS version 27. Foraging activity of out-foragers, in-foragers, and pollen foragers (measured at five sampling times: 7 am, 9 am, 11 am, 1 pm, and 3 pm; expressed as bee/colony/minute), quadrat-based bee density (bee/m^2/minute), and colony performance metrics (adult bee population, sealed brood area, pollen, and honey area) were analyzed using linear mixed models (LMM). In all models, sampling date and time of day (for foraging variables) were included as fixed factors, with colony identity as a random intercept to properly account for repeated measures on the same colonies over time. Fixed effects were evaluated using F- and p-values derived from Type III sums of squares, with denominator degrees of freedom estimated via the Satterthwaite approximation. Post hoc pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test, with the significance threshold set at $\alpha = 0.05$. Pearson product-moment correlation coefficients were computed to examine relationships among meteorological variables, foraging activity, and colony performance. Results are reported as estimated marginal means ± standard error (EMM ± SE) obtained from the LMM framework, or as arithmetic means ± standard deviation (SD) where otherwise indicated.

RESULTS

Foraging activities

Figure 1 illustrates the foraging dynamics of *A. mellifera* colonies in a basil (*O. basilicum*) field, presenting out-forager (Fig. 1A), in-forager (Fig. 1B), and pollen-foraging (Fig. 1C) activities quantified as bees per minute per colony in Assiut Governorate, Egypt. All foraging activity variables were analysed consistently using Linear Mixed Models (LMM) with colony as a random intercept. Observations were conducted on six dates from mid-summer to early autumn-2023 (10 July, 25 July, 9 August, 25 August, 8 September, and 25 September), with measurements recorded at five diurnal time points (7 am, 9 am, 11am, 1 pm, and 3 pm).

Out-foraging activity (Figure 1A) showed significant effects of sampling date ($F = 4.23$, df = 5, 18.7, $P = 0.009$) and time interval ($F = 28.56$, df = 4, 152.3, $P < 0.001$), with a significant date × time interaction ($F = 2.89$, df = 20, 156.4, $P = 0.002$). Activity ramped up from 7 am (estimated marginal mean [EMM] = 8.4 ± 1.2 bee/min/colony) to peak at 11 am and 1 pm (EMM = 38.7 ± 2.1 and 36.2 ± 1.9, respectively), before declining by 3 pm (EMM = 12.5 ± 1.4). Seasonal trends showed peak activity in July (EMM = 34.2 ± 2.4) declining to negligible levels by September (EMM = 3.8 ± 1.1). Random effects variance components indicated moderate colony-level variation (colony intercept variance $\sigma^2 = 28.4$, residual variance $\sigma^2 = 156.2$).

In-foraging activity (Figure 1B) similarly exhibited significant fixed effects for date ($F = 5.67$, df = 5, 19.2, $P = 0.002$), time ($F = 32.14$, df = 4, 148.7, $P < 0.001$), and their interaction ($F = 3.42$, df = 20, 151.9, $P < 0.001$). Early July showed elevated morning activity at 7 am (EMM = 40.2 ± 2.8), while later dates (August–September) shifted peak activity to afternoon intervals, with the highest recorded return rate exceeding 50 bee/min/colony at 3 pm on September 8.

Pollen foraging activity (Figure 1C) showed significant fixed effects for date ($F = 14.22$, df = 5, 18.9, $P < 0.001$), time ($F = 18.93$, df = 4, 153.1, $P < 0.001$), and their interaction ($F = 2.56$, df = 20, 155.8, $P = 0.001$). Peak pollen collection occurred at 11 am–1 pm in July (EMM = 32.5 ± 2.2) and August (EMM = 28.3 ± 2.4), with sharp declines by September (EMM = 4.2 ± 1.0). Random effects showed substantial colony-level variation in pollen foraging propensity (colony intercept variance, $\sigma^2 = 42.7$; residual variance, $\sigma^2 = 118.4$).

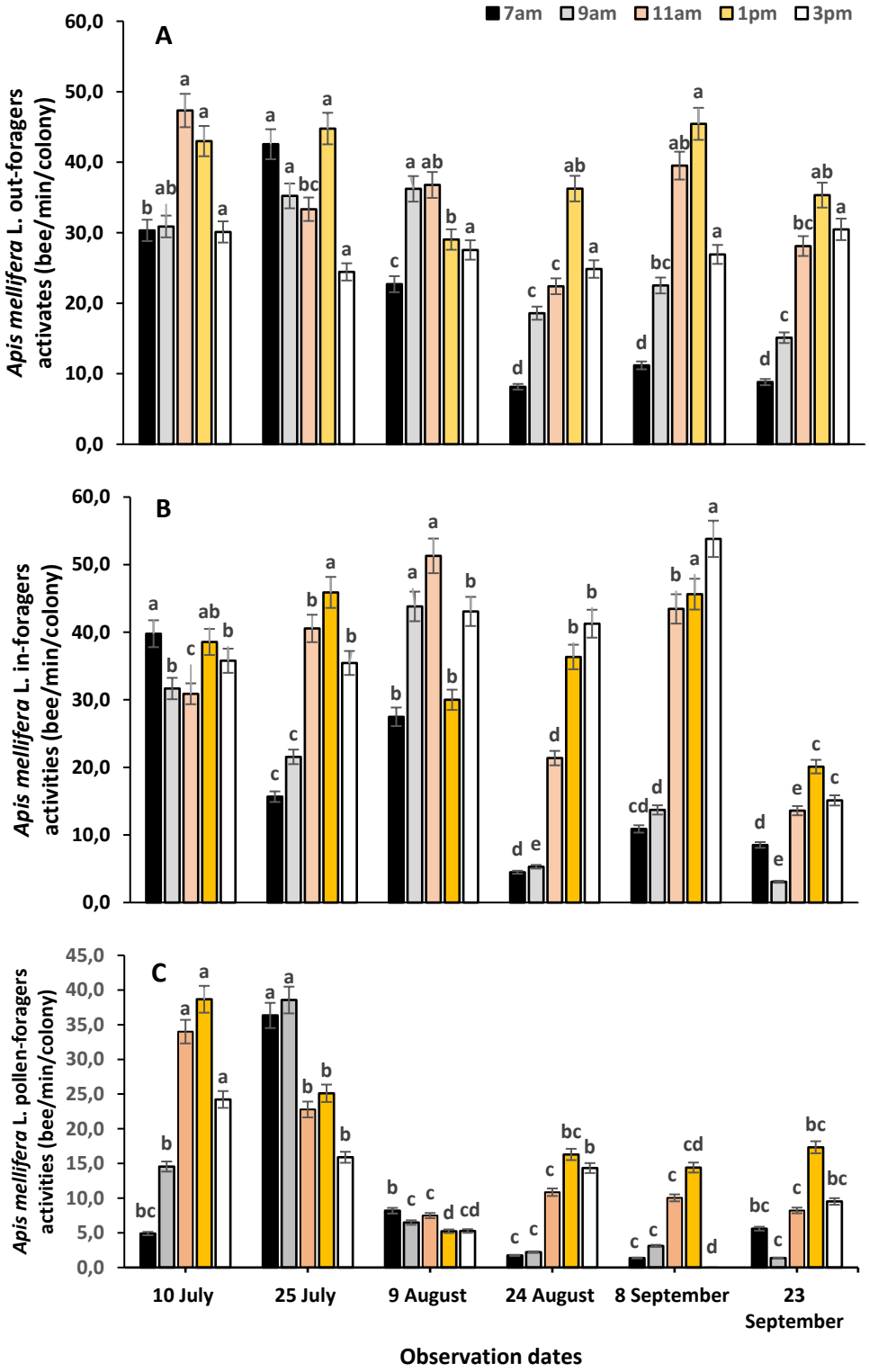

Figure 1: Seasonal and diurnal dynamics of *Apis mellifera* L. out-foraging (A), in-foraging (B) and pollen foraging (C) activities (bee/min/colony) on *Ocimum basilicum* L. field at five daily observation periods (7 am, 9 am, 11 am, 1 pm, and 3 pm) during the 2023 flowering season, in Assiut, Upper Egypt. Data are estimated marginal means (EMM) from Linear Mixed Models (LMM) with colony as a random intercept; error bars = SE. Bars with different letters within each time interval differ significantly (Tukey's HSD, P<0.05).

Diurnal temporal foraging dynamics of *A. mellifera*

Figure 2, illustrating the density of forager bees (forager bees No./m^2/min.) observed at five distinct diurnal time points 7 am, 9 am, 11 am, 1 pm, and 3 pm, across six observation dates ranging from July 10 to September 23 in *O. basilicum* fields in Assiut Governorate, Egypt. This temporal span covers the late summer to early autumn period, a critical phase in the annual cycle of basil flowering period. Significant effects were detected for date ($F = 32.67$, $df = 5, 18.2$, $P < 0.001$), time ($F = 41.23$, $df = 4, 149.6$, $P < 0.001$), and their interaction ($F = 4.18$, df

= 20, 152.4, P < 0.001). Initial bee densities on July 10 peaked at >40 bee/m²/min at 9 am, maintaining 30–40 bee/m²/min through the morning. Activity declined progressively across the season, with densities falling below 5 bee/m²/min by September 23. Random colony effects accounted for 23% of the residual variance (colony intercept σ² = 18.9, residual σ² = 62.4).

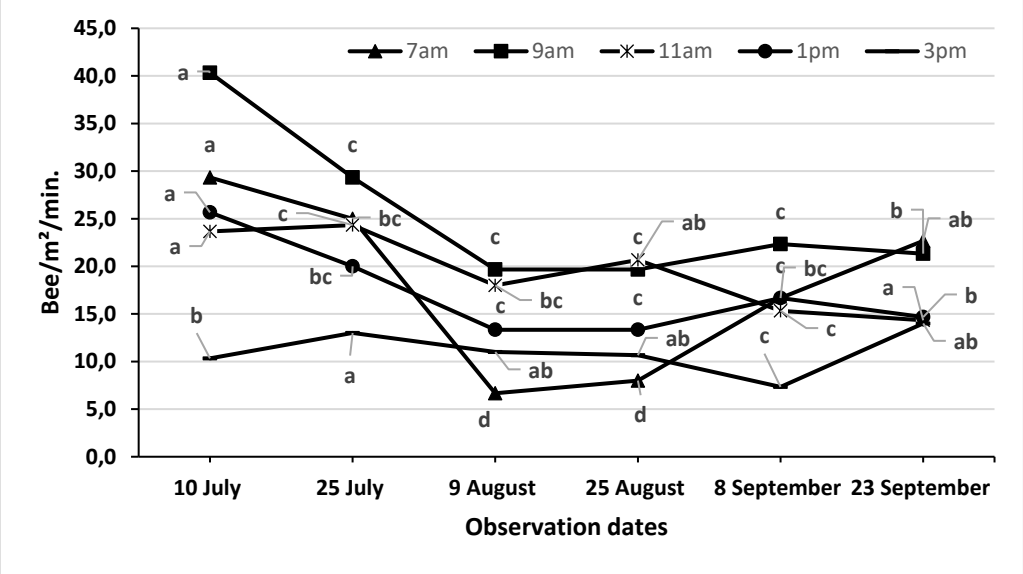

Figure 2: Diurnal patterns of *Apis mellifera* L foraging activity (bee/m²/min) in *Ocimum basilicum* L. fields at five fixed intervals (7 am, 9 am, 11 am, 1 pm, and 3 pm), in Assiut region, Upper Egypt during the flowering seasons of 2023. Data are estimated marginal means (EMM) from Linear Mixed Models (LMM) with colony as random intercept; error bars = SE. Different letters within each time interval indicate significant differences (Tukey's HSD, P<0.05).

Colony metrics

Colony performance metrics showed clear temporal patterns across the flowering season (Table 1). Adult bee population increased significantly from early July to late August before declining slightly by late September (LMM: F = 5.12, df = 5, 95.3, P = 0.001). Sealed brood area followed a similar trajectory, reaching a maximum of 384 ± 34 sq. in²/colony on 24 August (LMM: F = 6.87, df = 5, 94.8, P < 0.001). Stored pollen area exhibited the strongest temporal variation, increasing from 34.33 ± 10.21 sq. in²/colony on 10 July to 160.67 ± 34.43 sq. in²/colony (more than four-fold) on 24 August before declining (LMM: F = 14.76, df = 5, 95.1, P < 0.001). Honey storage area increased progressively throughout the season but showed no significant change over time (LMM: F = 1.24, df = 5, 95.6, P = 0.298). Post-hoc Tukey's HSD tests indicated that the August peak values were significantly higher than early July values for bee population, sealed brood, and pollen area (P < 0.05).

Table 1: Means ± standard deviation of colony performance metrics (sq. in²/colony) of honey bee colonies foraging on sweet basil (*Ocimum basilicum* L.) during the period 10 July – 23 September 2023 in Assiut, Upper Egypt.

Date	Colony activities (mean ± SD) (sq. in²/colony)			
	Bee population number	Sealed Brood areas	Pollen areas	Honey areas
10-Jul	655 ± 31.22^{b}	298 ± 17.56^{bcd}	34.33 ± 10.21^{d}	145 ± 50.74^{b}
25-Jul	640 ± 51.96^{b}	228 ± 30.14^{d}	72.00 ± 11.53^{c}	173 ± 16.07^{ab}
09-Aug	853 ± 133.17^{a}	337 ± 47.26^{abc}	121.67 ± 20.21^{b}	280 ± 26.46^{a}
24-Aug	940 ± 183.30^{a}	384 ± 34.43^{a}	160.67 ± 34.43^{a}	332 ± 85.80^{a}
08-Sep	883 ± 85.05^{a}	350 ± 45.08^{ab}	101.67 ± 20.82^{bc}	288 ± 46.19^{a}
23-Sep	788 ± 12.74^{ab}	262 ± 68.25^{cd}	77.00 ± 16.64^{c}	287 ± 59.09^{a}
LMM F	5.12	6.87	14.76	1.24
P	0.001	<0.001	<0.001	0.298

Means in the same column followed by the same letter do not differ significantly (Tukey's HSD, P > 0.05). Sq. in²/colony = square inches per colony (Jeffree 1958). Values are raw means; statistical results are from Linear Mixed Models (LMM) with sampling date as a fixed factor and colony as a random intercept.

Environmental measurements

Figure 3 presents diurnal and seasonal trends in air temperature, relative humidity, and wind speed (Figure 3 A, B&C, respectively) recorded at five daily intervals (7 am, 9 am, 11 am, 1 pm, and 3 pm) over 76 days in Assiut Governorate, Upper Egypt (10 July–23 September 2023). Temperature (Fig. 3A)

shows a clear seasonal decline, from 35–42 °C in mid-July to 25–35 °C by late September, with afternoon readings consistently exceeding morning values, reflecting diurnal heating. Significant monthly variation was confirmed ($F = 3.21$, $df = 3, 72$, $P = 0.028$), likely driven by the ~10°C seasonal decrease. Relative humidity (Fig. 3B) fluctuated erratically (10–60%) with no distinct seasonal trend, but showed consistent diurnal inversions, with morning values (40–50%) higher than afternoon readings (20–30%). Wind speed (Fig. 3C) exhibited high variability, with baseline values of 2–5 m/s and a pronounced peak exceeding 8 m/s around 25 August. This anomaly contributed to highly significant monthly differences ($F = 43.22$, $df = 3, 72$, $P < 0.001$). Following this event, wind speeds declined to below 4 m/s by September.

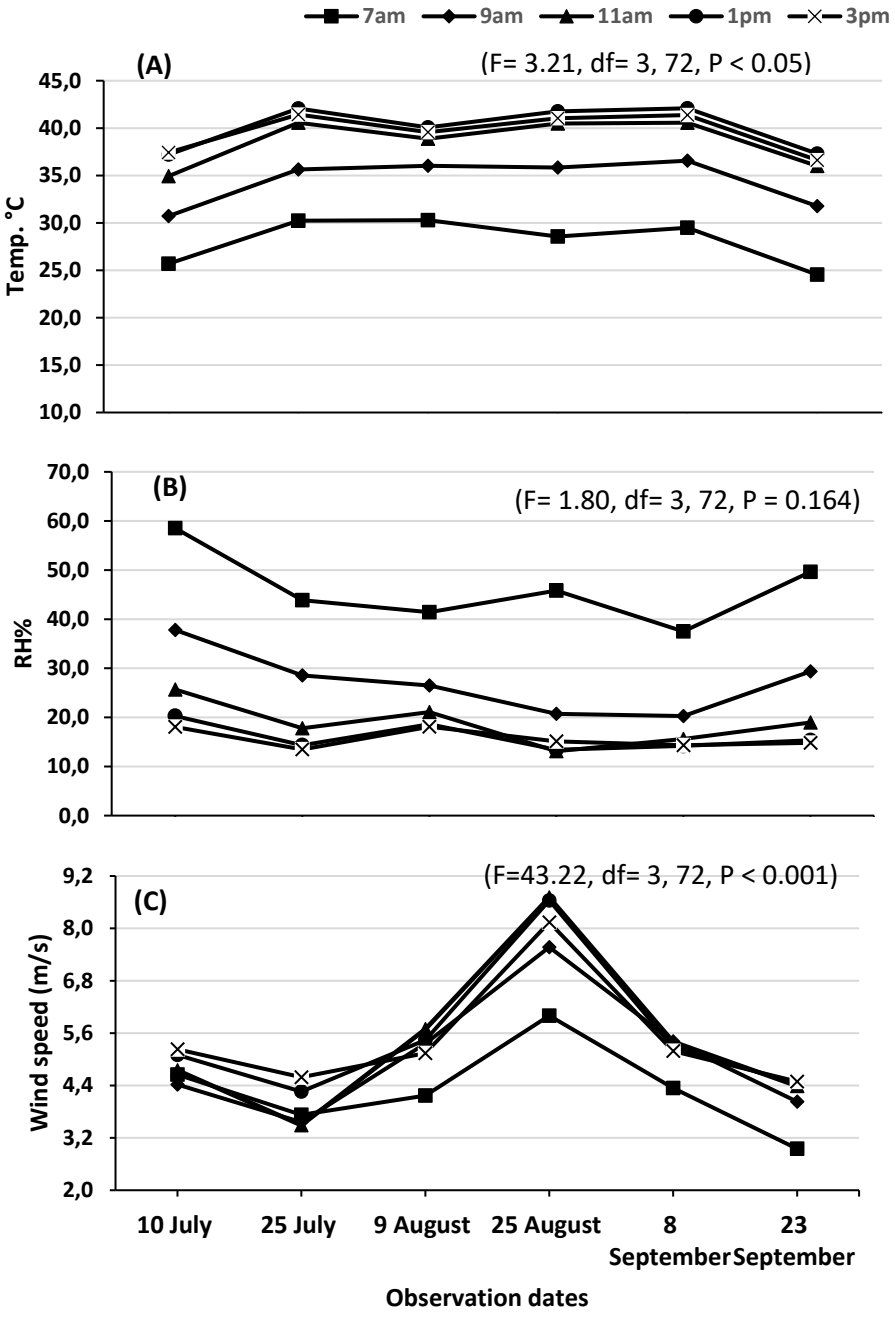

Figure 3: Daily fluctuation of climatic factors recorded across five daily observation periods (7 am, 9 am, 11 am, 1 pm, and 3 pm) over a 3-month period from July 10 to September 23, 2023. The measured parameters are air temperature (A, °C), relative humidity (B, %), and wind speed (C, m/s). For each parameter, a one-way Analysis of Variance (ANOVA) was used to compare monthly means; significant results ($P < 0.05$) were followed by a Dunn's post hoc test for pairwise comparisons.

Colony metrics, foraging activity and meteorological conditions relationships

Table 2 presents a Pearson correlation matrix analyzing relationships between internal *A. mellifera* colony metrics, population size (Pop), sealed brood area (SB), and stored honey (H) and pollen (P) areas (sq. in²/colony), and external factors during the 2023 basil (*O. basilicum*) flowering season in Assiut,

Upper Egypt. External variables include diurnal forager counts on basil and climatic parameters (air temperature ˚C, relative humidity %, and wind speed m/s). Air temperature shows varied associations, primarily non-significant with colony metrics but significantly negative with foraging activity, suggesting a thermal threshold effect on bee foraging behaviour. All correlations with forager numbers are negative and significant, with the strongest at 11 am (r = -0.636**, P < 0.01), followed by 9 am (r = -0.494*), 7 am (r = -0.444*), 1 pm (r = -0.452*), and 3 pm (r = -0.246*). Between bee foraging behaviour and wind speed (m/s), a highly significant negative correlation at 7 am (r = -0.684**, P < 0.01) contrasts with non-significant, mostly negative values later (9 am: r = -0.265; 11 am: r = 0.070; 1 pm: r = -0.312; 3 pm: r = -0.366). However, wind speed was significantly positively correlated with bee population (r = 0.612, P < 0.01) and sealed brood area (r = 0.748, P < 0.01), whereas relative humidity showed only non-significant negative trends with all measured colony parameters.

Strong positive correlations among colony metrics (Table 2) bee population with honey (r = 0.95), pollen (r = 0.88), and brood (r = 0.85); pollen with honey (r = 0.86) reflect coupled nutritional dynamics. However, the August peak in pollen collection a ~4.7-fold increase from July 10 to August 24 coincides with basil's full bloom. These interdependencies warrant future explorations via path analysis or structural equation modeling.

Table 2: Matrix of Pearson correlation coefficients (r) for *Apis mellifera* L. colony population size (Pop), areas of workers sealed brood (SB), stored honey (H), pollen (P), bee forager No. on basil (*Ocimum basilicum* L.) flowers at five daily observation periods (7 am, 9 am, 11 am, 1 pm, and 3 pm) and climatic parameters of air (Air Temp. ˚C), relative humidity % (RH%) and wind speed (WS) m/s, in Assiut, Upper Egypt, during 2023 flowering season. The asterisks indicate significant correlations (*p<0.05 = significant, **p<0.01 = high significant, ***p<0.0001 = very high significant.

	Colony Metrex (r)				Bee forager No. on basil flowers (r)				
	Pop	SB	P	H	7am	9am	11am	1pm	3pm
Air Temp. ˚C	0.077	0.054	0.492*	0.229	-0.444*	-0.494*	-0.636**	-0.452*	-0.246*
RH%	-0.144	-0.036	-0.400	-0.200	0.329	0.385	0.309	0.271	0.188
WS	0.612**	0.748**	0.360	0.124	-0.684**	-0.265	0.070	-0.312	-0.366

P > 0.05 considered non-significant, P < 0.05 = * (significant) and P < 0.01 = ** (high significant).

DISCUSSION

This study documented the diurnal and seasonal foraging dynamics of *A. mellifera* on *O. basilicum* in an arid region of Assiut, Upper Egypt, quantified associated changes in colony performance, and examined the influence of key meteorological variables. The results support hypotheses H1, H2, and H3, while providing only partial support for H4.

Foraging activity showed a clear bell-shaped diurnal pattern, with peaks between 11 am and 1 pm in July (30–45 bees/min/colony) and a sharp seasonal decline by late September (<5–10 bees/min/colony). This pattern is consistent with optimal conditions for flight and resource location in the morning (Amro 2023). A prominent feature of the data (Fig. 2) is the progressive decline in forager density (bee/m²/min) from mid-July to late September, reflecting seasonal phenological shifts in temperate bee populations. An additional factor in the decline of foraging bee populations may be the concentration of nectar sugar. Sharif et al. (2020) reported that although honey bees exhibit a preference for richer food sources (e.g., 50% sugar), visits to these high-concentration feeders decrease over time, possibly because increased viscosity reduces feeding efficiency. Also, the same previous authors found that, both resource quality and prior experience intrinsically shape honey bee foraging persistence and performance. As summer wanes, floral resources diminish due to plant senescence, creating a "dearth period" of scarce nectar and pollen (Amro 2009). This seasonal attenuation may have significant consequences. Because foraging efficiency is critical to colony fitness, the observed reductions potentially pose a risk to overwintering survival (Rodney & Purdy 2020).

The post-August decline in pollen foraging (Fig. 1C, Table 1) coincided with reduced sealed brood area (r = 0.85; Table 2), reflecting the nutritional dependence of brood rearing on protein inputs (Bryś & Strachecka 2024). As demonstrated by Tsuruda and Page (2009), pollen influx correlates strongly with brood area early-season peaks that support larval feeding, whereas late-season lows signal a shift to nectar hoarding for winter stores (Mačukanović-Jocić et al. 2008). The subsequent decline in foraging (out, in and in pollen foragers) and colony metrics by September reflects the natural end of the basil flowering period and the transition toward autumn conditions in Upper Egypt. Along the same lines, Sharif et al. (2020) documented that when food richness at a familiar site decrease, forager numbers gradually decline, yet bees continue visiting unrewarding sites for several days, showing strong attachment to previous rewarding locations. This persistence can be explained by honey bee forager flower constancy (Çakmak et al. 2009, Sanderson & Wells 2005, Omran et al. 2026).

To elucidate drivers of pollination efficacy, we correlated diurnal foraging activity and colony performance metrics of *A. mellifera* on *O. basilicum* with concurrent meteorological variables. The

resulting correlations highlight trade-offs between colony maintenance and foraging efficiency. Air temperature was negatively correlated with foraging activity, particularly at 11 am ($r = -0.636$, $P < 0.01$), indicating reduced foraging under high daytime temperatures (Amro et al. 2023). Wind speed showed a strong negative association with early-morning foraging ($r = -0.684$, $P < 0.01$). But, relative humidity had no significant effect on any variable. suggesting a minor facilitative role in reducing desiccation, though humidity was not a primary driver in this context contrasting with its inhibitory effects in more humid environments (Abou Shaara et al. 2017). Conversely, morning winds imposed a key foraging limitation by increasing flight energetic costs in dense, cool air (Hennessy et al. 2020). Though direct internal measurements inside the honey bee colonies are needed to confirm mechanisms. Notably, meteorological data were sourced 500 m from basil plot; we acknowledge that within canopy microclimates may differ from ambient recordings (Pincebourde et al. 2017). However, station proximity and temporal alignment mitigate major discrepancies. Future research should employ in situ sensors to capture fine scale environmental gradients and enable precise modeling of microclimatic effects on foraging behavior.

In this study, colony performance metrics followed distinct seasonal trajectories: adult bee population, sealed brood area, and pollen stores peaked in late August before declining, whereas honey stores increased steadily without significant temporal change. Also, our results documented that, the mid-season peak in colony strength (late August) coincided with the period of highest cumulative foraging effort earlier in the season, demonstrating that sweet basil provided a valuable forage resource that supported colony buildup during the summer. This pattern is consistent with previous observations by Omer et al. (2008) on basil in Upper Egypt, in which colony metrics peaked in August, coinciding with maximal nectar and pollen availability from basil inflorescences. However, in early to mid-July, peak activity coincided with higher ambient temperatures and maximum nectar secretion or pollen dehiscence in basil (Abrol et al. 2017, Mačukanović Jocić et al. 2008). Notably, sustained high activity as late as 25 September (peaking at 35 bee/min/colony at 1 pm) underscores the value of *O. basilicum* as a critical late season forage resource for winter preparation.

The present results confirm that *O. basilicum* serves as an important late-summer forage plant for honey bees in the arid region of Assiut, Egypt. However, the pronounced boom-and-bust pattern in foraging and colony performance highlights the colonies' vulnerability to temporal fluctuations in resources. These findings suggest that maintaining floral resource continuity through diversified planting may help stabilize colony development in regions with limited summer forage. Further experimental studies are needed to test the effects of forage diversity and supplemental planting on colony resilience in similar arid environments.

Conclusion

This study demonstrates that sweet basil (*Ocimum basilicum* L.) serves as a vital late-summer forage resource for honey bees (*Apis mellifera* L.) in Assiut, Upper Egypt. Intense foraging activity in July, peaking diurnally at midday, drives resource influx that supports peak colony development in August, including significant increases in adult population, sealed brood, and pollen stores. The subsequent decline in foraging and brood rearing by September reflects seasonal resource senescence and colony preparation for winter. Air temperature and wind speed significantly influenced foraging activity, whereas relative humidity had a minimal effect. These findings indicate that basil supports colony buildup during summer in Assiut; however, the marked late-season decline in foraging underscores colony vulnerability to resource scarcity at the end of flowering. These findings suggest that maintaining continuity of floral resources may help reduce periods of forage dearth in arid regions. Nevertheless, because this study was conducted at a single site during a single season, further multi-year, multi-site experimental studies are needed to confirm these patterns and evaluate the effectiveness of forage diversification strategies.

AI Declarations: All authors declare that the manuscript has not been prepared by AI.

Authors' contributions: AMA, ZHA, SMA, and AMA help with planning, data gathering, methodological planning, experimentation, and putting up a study. All authors read and approved the final manuscript.

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