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Impact of honey bee (*Apis mellifera* L.) pollination and selected biostimulant extracts on seed production of onion (*Allium cepa* L.) in New Valley, Egypt

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Abstract

This study evaluated the combined effects of honey bee (*Apis mellifera* L.) pollination and foliar applications of natural biostimulant extracts on onion (*Allium cepa* L.) seed yield and quality in New Valley Governorate, Egypt, during the 2023 and 2024 seasons. Field experiments employed a randomized complete block design, testing extracts from molasses, licorice, wormwood (*Artemisia*), and old beeswax combs, alongside water spray, pollinator exclusion (tulle bagged umbels), and an untreated control. Managed Carniolan honey bee colonies facilitated pollination. Honey bee foraging activity displayed significant diurnal variation, peaking between 11:00 and 13:00, with intensity increasing seasonally from March to May, and was positively and negatively correlated with temperature and humidity, respectively. Old beeswax comb extract proved most effective, significantly enhancing bee visitation, yielding the highest seed production (163.8–172.2 kg/ha., representing an over 100% increase compared to the control), the lowest sterility (4.6–6.4%), and the highest germination (94.5–96.3%). Molasses and licorice extracts also markedly improved yield (28–38% increase) and fertilization rates (up to 84.5%). Pollinator exclusion drastically reduced yield and quality, underscoring bees' essential role. Integrating managed honey bee pollination with the application of old beeswax comb extract offers a sustainable strategy to substantially improve onion seed quantity and quality in arid agroecosystems.

Keywords: *Allium cepa* L. yield parameters, *Apis mellifera* L. foraging, Beeswax, Licorice extract, Molas extract

INTRODUCTION

Onion crop (*Allium cepa* L.) is one of the most important vegetable crops all over the world. In Egypt, it is used for local consumption and processing, as well as for exportation. Most of the exported onion crop products are shipped to the European and Arab markets in their fresh form or as dehydrated products. This was mainly due to the good reputation of the Egyptian onion genotypes and their products in these markets. Onion is grown in Egypt as a winter, summer and fall crop either as a single or intercropped plantation (Al-Marsomy and Gharbi 1999).

The commercial production of onion seed is fundamentally dependent on effective pollination. Among pollinators, bees provide the most critical service, with honey bees alone accounting for approximately 90% of this activity (Mabrouk and Mahbob 2017, Amro 2021). They meet their nutritional requirements by collecting pollen for a

vital protein source and nectar for carbohydrates. Deploying managed honey bee colonies is both cost-effective and ecologically sustainable for enhancing seed yield and quality in onion and other cross-pollinated crops. This approach not only increases seed quantity but also improves seed quality, as evidenced by higher germination rates in bee pollinated seeds (Gupta 2012). Consequently, fostering robust honey bee colonies is of dual importance: it ensures the pollination services required for viable seed production while simultaneously supporting apicultural enterprises focused on honey yield (Lin et al. 2025).

The honey bee (*Apis mellifera* L.) serves a crucial ecological function as a pollinator. By transferring pollen grains between flowers of the same or different plants, a process defined as pollination supports the reproduction of wild flowering plants and the productivity of many agricultural crops (Kalmath and Sattigi 2005). Honey bees are an

essential biotic agent in onion seed production, acting as highly proficient pollinators. Their foraging behaviour on onion inflorescences significantly enhances both seed yield and quality relative to open pollination or pollinator-excluded environments (Korichi et al. 2023). This enhancement is attributed to the efficiency of honey bees in pollen transfer, which facilitates superior seed set and maximises quantitative yield (Pushpalatha et al. 2023).

Onion (*Allium cepa* L.) flowers attract pollinators primarily through nectar rewards and floral volatile organic compounds (VOCs), which are critical for enhancing visitation rates and improving seed production in this entomophilous crop (Kalmath and Sattigi 2005, Lin et al. 2025). Nectar serves as the main reward, providing sugars, phenols, and alkaloids that influence honey bee preference, with variations in composition such as higher sucrose or specific phenols correlating with increased bee visits and higher seed yields in open pollinated lines compared to hybrids (Soto et al. 2013).

Floral VOCs, including monoterpenes like linalool and benzaldehyde derivatives, act as olfactory cues that guide pollinators from a distance, while certain organosulfur compounds or dioxolanes in male-sterile lines may repel bees, reducing pollination efficiency (Soto et al. 2015). Differences in nectar volume, sugar concentration, and volatile profiles among cultivars directly affect foraging behavior, with more attractive lines showing greater bee visitation and up to 60% higher seed set (Soto et al. 2023). High potassium levels in nectar can deter bees, further emphasizing the role of balanced chemical composition in attraction (Sengupta and Ghorai 2018). Recent studies highlight generalist volatiles, such as trans- β -ocimene, that draw diverse insects, including scoliid wasps, broadening pollination networks (Divija et al. 2024).

External attractants, such as olive pomace water extracts rich in phenolics, have been shown to increase honey bee visits and seed yields when applied to umbels (Monasterio et al. 2023). Morphological traits, such as larger tepals and styles, complement these chemical signals by enhancing visual and tactile cues (Soto et al. 2013). Overall, optimizing nectar rewards and reducing repellent VOCs through breeding or attractant applications can significantly elevate pollinator activity and onion seed production (Prasad et al. 2000).

The highest productivity and best-quality onion crops were achieved through improved seed quality, in combination with agricultural practices and treatments. Therefore, many techniques are used, such as spraying extracts to attract pollinators to the onion flowers and increase seed production (Monasterio et al. 2023).

The present study therefore aimed to: (i) quantify the foraging activity of honey bee workers during onion flowering; (ii) evaluate the contribution of bee pollination to the physical traits and yield of onion

seeds; and (iii) assess the effect of foliar applications of selected bio-stimulant extracts on the attractiveness of onion flowers to bees, with the goal of improving pollination efficiency, fertilization rates, and seed germination success.

MATERIAL AND METHODS

This study was conducted at the Plant Protection Department, Faculty of Agriculture, Sohag University, Egypt, over two consecutive growing seasons 2023 and 2024. The field trials were conducted on a private farm in the villages of Al-Hindaw and Al-Rashda, in the New Valley Governorate, Egypt (Figure 1).

Experimental site and design

The selected field for onion transplant was on the first of December 2022. A randomized complete block design (RCBD) was used with six treatments with three replications in addition to the control treatment. One plot was used for each replicate and three replicates were used for each treatment. Each plot consisted of 6 rows, each measuring 9 m². Onion transplants were planted on the two sides of each row at a distance of 25 cm apart (4 plants per meter), and the number of plants per row was equal to 12 plants, resulting in a total of 72 per plot. The six treatments were: molasses extract, licorice extract, wormwood (*Artemisia*) extract, old bee wax extract, spring water, tulle bagging, and control.

Preparation of extract

All extracts (molasses, licorice, wormwood, old beeswax comb) were applied immediately after preparation to preserve bioactivity and prevent degradation. When immediate use was not possible, extracts were stored in sterile glass containers at 4°C for up to 24 h; any remaining extracts beyond this period were discarded and freshly prepared. Foliar applications commenced at flowering onset (early March, ~30–40% umbel opening) using a 20-L hand held compressed air sprayer calibrated for uniform mist delivery.

Three consecutive sprays were performed at 10-day intervals during the flowering period (early March to mid-April) in both seasons (2023 and 2024). Application dates were 5, 15, and 25 March in 2023, and 3, 13, and 23 March in 2024. Spraying occurred during early morning (06:00–08:00 h) to minimize evaporative loss under high local temperatures, avoid peak bee foraging (11:00–13:00 h), and maximize foliar absorption before midday heat according to Omran et al., (2025). Each plot received ~2 L of extract solution per application, ensuring complete umbel and foliage coverage to run-off. The sprayer was rinsed thoroughly with distilled water between treatments to prevent cross-contamination. Control plots received an equivalent volume of distilled water under identical conditions.

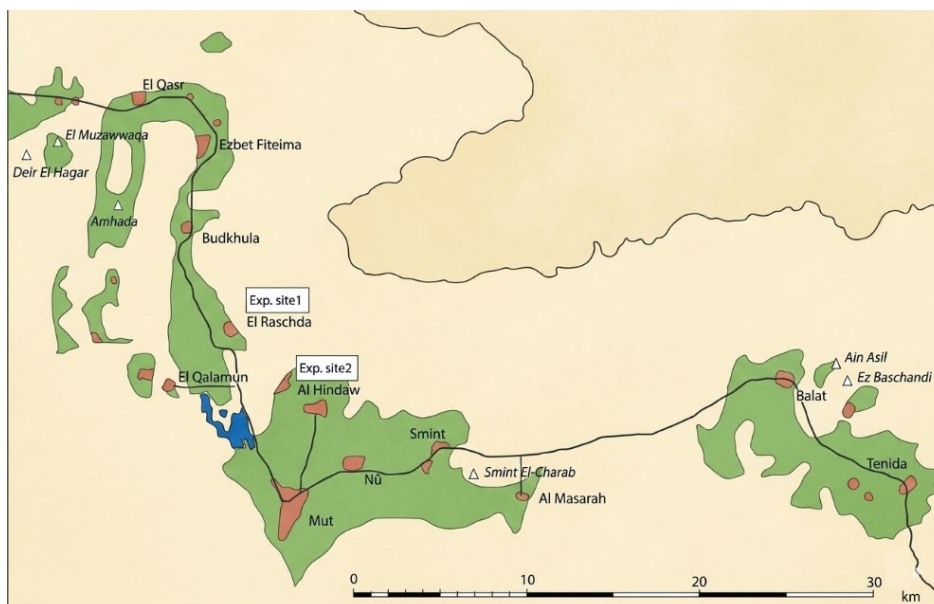


Figure-1. Map of Dakhla Oasis Experimental sites

Molas extract: To prepare the solution, 10 cm³ of sugarcane molasses was added to 1 litre of distilled water and thoroughly mixed using an electric mixer for one minute. The resulting solution was then ready for use.

Licorice extract: Licorice extract was obtained using the methodology used by (Al-Marsomy and Gharbi 1999): licorice roots were ground and sieved, and the obtained fine powder was placed in a liter of distilled water at a temperature of 50°C for 15 minutes to prepare the required concentration (10 g /litre). Then, using an electric mixer, the mixture is left for 24 hours, and filtered several times until the extract is obtained for use.

Wormwood extract (*Artemisia*): Wormwood plant material was brought from a herbalist, air-dried, finely ground, and sieved to obtain a uniform powder. An accurately weighed amount of the powder (10 g L⁻¹) was added to hot distilled water and allowed to cool to room temperature. The resulting suspension was homogenized using an electric mixer for 15 min, then left to macerate for 24 h under laboratory conditions. The extract was subsequently filtered several times to remove particulate matter, yielding a clear aqueous extract.

Old beeswax extract: Old beeswax was cut into small pieces, sealed in moisture-proof plastic bags, and stored in the freezer (-5°C) for 48 h. The frozen material was then finely ground using a coffee grinder and subsequently sieved to obtain a homogeneous powder. An accurately weighed amount of the powder (10 g L⁻¹) was suspended in distilled water to prepare a ready-to-use aqueous extract.

Water treatment: In this treatment, the experimental plot was sprayed with water only using a sprayer to increase the humidity level around the umbels of the onion but the control treatment was left unprocessed.

Covered inflorescences: This treatment was isolated from insect pollinators by tulle-bagging the umbel, and the control treatment was left unprocessed. Pollinators were excluded from a subset of ten plants (n=10) by covering them with bags made of 2 mm tulle mesh. This material was chosen for its dual purpose: physically barring insect visitors while ensuring sufficient ventilation for the enclosed plants.

Preparing the honey bee colonies

Six colonies of Carniolan honey bee colonies were chosen in a private apiary in El-Rashda Village, Dakhla Oasis. These colonies contained 6 brood combs covered with bees and food combs and each colony was headed by a one-year-old mated queen. Three control colonies were maintained in the private apiary and the remaining three colonies, designated for onion flower pollination, were relocated to the experimental site within onion fields in Al-Hindaw Village (Dakhla Oasis), situated approximately 1 kilometer from the control apiary. The temperature and relative humidity were continuously recorded at the time of observation at the experimental site, and the resulting data were tabulated and analyzed.

Diurnal and seasonal foraging activities

Foraging activity was assessed via visual counts of outgoing workers at the entrance of each colony. Observations were conducted weekly over a 10-week period during the 2023 and 2024 study years (10 March – 22 May), with five replicate measurements obtained on a single designated sampling day per week.

Throughout the study, outgoing foragers were counted at 2-h intervals from 07:00 to 17:00 h. At each interval, five successive 1-min observations were made per colony, and the average number of

bees departing per colony per 1 min was calculated. This protocol yielded a representative sample size suitable for quantifying foraging dynamics, consistent with Nye and Mackensen (1970).

Foraging dynamics of honey bees in onion fields

Following Amro (2021), the foraging activity of *A. mellifera* was assessed weekly throughout anthesis via direct observation. Counts were performed at 2-h intervals from 07 am to 5 pm using a 1 m² wooden quadrat, and forager abundance was expressed as bees per plant per minute. Mean values were subsequently calculated for each sampling interval.

Physical characters

A sample of one square meter was taken randomly of each replicate of all treatments to determine the physical characters of onion seed such as, average number of scape/plants, average of air dry weight of seed scape, average of 1000 seed weight, average weight of one umbel of seed, average weight of experimental plot (9 m²). Seed yield is estimated from the harvest plot area after over-drying. The samples were cleaned and weighed. The number of seeds per plant was counted by selecting a random 1 m² area from each treatment and expressed as the number of seeds per umbel. After maturity, the umbels of each plant were harvested individually, and the seeds were separated by thrashing the umbels and the weight was recorded using an electronic balance and is expressed in grams/square

meter. The test weight of onion seed was determined by weighing 1000 dried seeds drawn randomly from each treatment using an electronic balance. At the end of the experiment, the yield component of the hectare was estimated.

Seeds germination percentage.

To assess seed quality, germination tests were conducted immediately after harvesting and processing (June–July of each respective year) to prevent viability loss. From each treatment replicate (three per treatment), 100 apparently healthy, undamaged seeds were randomly selected, for a total of 300 per treatment. Following Amro (2021), seeds were surface-sterilized in 1% sodium hypochlorite for 2 min, rinsed thrice with distilled water, and placed evenly in 9-cm glass Petri dishes (20 seeds·dish⁻¹, five dishes/replicate) lined with two layers of *Whatman* No. 1 filter paper. Each dish received 5 mL distilled water initially, with 2–3 mL added every 48 h as needed to maintain moisture without waterlogging.

Dishes were incubated for 14 days in a growth chamber (Binder GmbH, Germany) at 20 ± 1°C, 70 ± 5% RH, and a 12 h photoperiod (~1000 lux, cool white fluorescent lamps). Seeds exhibiting fungal growth were removed immediately and recorded; dishes were repositioned randomly every 48 h to minimize positional effects. Germination percentage of seeds was calculated using the following formula:

$$\text{Germination (\%)} = \frac{\text{Number of germinated seeds in petri dishes}}{\text{Total number of seeds used for germination}} \times 100$$

Meteorological data

The meteorological data were obtained from the Kharga Oasis meteorological station in New Valley, including maximum and minimum temperatures, relative humidity (RH), wind speed, and the sunshine period. Weekly weather data, including maximum, minimum, and mean temperature, mean relative humidity, precipitation, and wind speed, were

recorded for the 2023 and 2024 seasons. The data were collected each week from March 1st to May 31st.

Yield increase percentage

Yield increase (%) was calculated for each biostimulant treatment relative to the untreated control, enabling direct comparison of efficacy across seasons while accounting for baseline yield variation. The yield increase percentage was calculated using the following formula:

$$\text{Yield Increase (\%)} = [(Y_t - Y_c) / Y_c] \times 100$$

Where:

- Y_t = Mean seed yield (kg/ha) of the treatment plot (e.g., molasses, licorice, wormwood, old wax combs)

- Y_c = Mean seed yield (kg/ha) of the untreated control plot.

Fertilization rate

The fertilization rate (also referred to as fruit set percentage or seed set efficiency) was calculated to assess pollination effectiveness across different treatments. This parameter reflects the proportion of flowers that successfully developed into seeds. At

physiological maturity (umbels browning, seeds fully developed), ten plants per replicate (n = 3) were randomly selected, and one primary umbel per plant was harvested. This yielded 30 umbels per treatment (10 plants × 3 replicates) for analysis. Total florets per umbel were quantified prior to

threshing by counting pedicel scars on the receptacle. Each scar corresponds to a single flower, whether fertilized (seed-producing) or unfertilized (aborted/sterile). Following pedicel scar counts, each umbel was gently threshed to extract developed seeds. After cleaning, the total number of

filled, apparently viable seeds were counted using an electronic seed counter (Pfeuffer Contador, Germany) or manually for small samples. The fertilization rate was calculated using the following formula:

$$\text{Fertilization Rate (\%)} = \frac{\text{Number of developed seeds per umbel}}{\text{Total number of flowers per umbel}} \times 100$$

Where:

- Number of developed seeds per umbel = Mean count of filled seeds from the 30 sampled umbels per treatment
- Total number of flowers per umbel = Mean count of pedicel scars from the same 30 umbels

Sterility percentage

For comparative purposes, the sterility percentage (the inverse of fertilization rate) was also calculated as:

$$\text{Sterility (\%)} = [(\text{Total flowers} - \text{Developed seeds}) / \text{Total flowers}] \times 100 = 100 - \text{Fertilization Rate}$$

Statistical analysis

The obtained data were statistically analyzed using analysis of variance (ANOVA) for a randomized complete block design (RCBD) according to Snedecor and Cochran (1973). Prior to analysis, data were tested for normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) to ensure compliance with ANOVA assumptions. When significant differences among treatments were detected ($P < 0.05$), means were compared using Tukey's Honestly Significant Difference (HSD) test at the 5% probability level. Results are presented as mean \pm standard deviation, and treatments within each column followed by the same letter indicate no significant difference at $P < 0.05$ according to Tukey's HSD test. Correlation coefficients (r) between foraging activity and weather factors were calculated using Pearson's correlation analysis, and multiple regression analysis was performed to determine the combined effects of temperature and humidity on foraging activity.

RESULTS

Diurnal and seasonal foraging activities

A statistical analysis of the overall means from Table 1 confirmed a significant variation in foraging activity in onion fields during the 2023 season throughout the day ($F = 25.67$, $P = 0.001$). The data reveal a characteristic bimodal pattern, with activity rising from a low morning at 7 am. (40.15 ± 18.23 bee/colony/min) to a primary peak at 9 am. (53.15 ± 21.45 bee/colony/min). The activity remained high through 1 pm. (53.15 ± 19.23 bees/min) before

declining significantly by late afternoon to 5 pm. (40.15 ± 16.78 bee/colony/min). As clearly illustrated in Table 1, a strong, statistically robust seasonal trend was evident. Foraging activity substantially increased from March to May. The lowest activities were recorded in early March (e.g., overall mean on 10-Mar: ~ 15 bee/colony/min), while the season's highest single recording was 85.67 ± 1.53 bees/min at 1 pm. on May 15.

The mean number of outgoing foragers (bees/colony/min) at 2-h intervals during the 2024 onion flowering period is shown in Table 2. The analysis of data revealed a highly significant diurnal variation ($P = 0.001$) in the number of foraging honey bee workers (*A. mellifera*). A clear daily foraging pattern was observed, with peak activity occurring during mid-morning (9 – 11 am) and early afternoon (1 pm). Conversely, the lowest activity levels were recorded in the early morning (7 am) and late afternoon (5 pm).

The overall mean values summarized in Table-2 show that the highest foraging activity occurred at 1 pm (25.34 ± 11.23 bee/colony/min), while the lowest occurred at 5 pm (10.23 ± 7.34 bee/colony/min). It is noteworthy that these values were considerably lower than the peak activity recorded in the 2023 season (53.15 ± 19.23 bee/colony/min), indicating a difference in foraging intensity between the two seasons. The results also revealed distinct seasonal dynamics, with foraging activity increasing progressively from March to May, peaking in the latter half of May (as evident in the data for May 4, 11, and 18).

Table-1. Diurnal and seasonal foraging activity patterns of honey bees (*Apis mellifera* L.) during flowering periods (Mean number of bee/colony/min ± SD) in Onion fields in the 2023 season.

Date	Mean number of forager bees ± SD (bee/colony/min)						F value	P value	LSD
	7 am	9 am	11 am	1 pm	3 pm	5 pm			
10-Mar	5.33 ± 2.52	15.33 ± 5.51	25.33 ± 5.51	23.67 ± 1.53	11.67 ± 12.50	7.33 ± 1.53	18.45	<0.001	8.45
17-Mar	9.33 ± 1.53	17.00 ± 1.00	25.00 ± 2.65	26.00 ± 2.65	25.00 ± 2.65	7.00 ± 3.61	42.67	<0.001	5.23
24-Mar	12.33 ± 2.08	21.33 ± 2.52	28.33 ± 2.52	23.33 ± 1.53	23.33 ± 2.52	16.00 ± 1.00	32.89	<0.001	4.78
1-Apr	29.00 ± 5.57	31.33 ± 6.03	32.67 ± 1.53	48.00 ± 3.61	37.00 ± 11.53	44.33 ± 5.51	8.76	0.001	12.45
8-Apr	36.33 ± 5.51	53.67 ± 3.06	46.00 ± 2.65	45.67 ± 2.52	35.67 ± 3.06	43.33 ± 1.53	45.23	<0.001	6.34
15-Apr	54.00 ± 2.65	59.33 ± 4.73	49.00 ± 8.19	48.33 ± 1.53	33.67 ± 2.08	43.33 ± 0.58	36.78	<0.001	7.89
23-Apr	40.67 ± 3.06	75.33 ± 4.04	54.00 ± 2.65	47.67 ± 1.53	35.00 ± 2.65	44.33 ± 1.53	185.45	<0.001	5.12
30-Apr	47.00 ± 5.29	74.33 ± 3.51	63.00 ± 2.65	48.00 ± 2.65	34.00 ± 2.00	43.33 ± 2.52	112.34	<0.001	6.78
7-May	42.33 ± 3.06	76.67 ± 5.03	65.67 ± 2.52	53.67 ± 3.79	35.67 ± 2.52	52.00 ± 2.65	134.56	<0.001	6.45
15-May	57.00 ± 1.00	55.00 ± 3.61	63.67 ± 3.06	85.67 ± 1.53	72.33 ± 7.57	53.33 ± 1.53	78.90	<0.001	8.90
22-May	71.33 ± 2.52	56.00 ± 2.00	73.67 ± 2.52	81.00 ± 5.00	55.00 ± 2.65	54.00 ± 2.65	92.34	<0.001	7.23
Overall	40.15 ± 18.23	53.15 ± 21.45	51.82 ± 16.34	53.15 ± 19.23	38.15 ± 17.45	40.15 ± 16.78	25.67	<0.001	7.89
F value	25.67								
P value	0.001								
LSD	7.89								

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

Table-2. Diurnal and seasonal foraging activity patterns of honey bees (*Apis mellifera* L.) during flowering periods (Mean number of bee/colony/min ± SD) in Onion fields in 2024 season.

Date	Mean number of forager bees ± SD (bee/colony/min)						F value	P value	LSD
	7 am	9 am	11 am	1 pm	3 pm	5 pm			
2-Mar	13.33 ± 1.53	16.33 ± 2.08	26.00 ± 2.00	26.67 ± 5.51	15.67 ± 4.04	7.33 ± 1.15	25.67	<0.001	4.56
9-Mar	16.56 ± 2.03	17.00 ± 3.61	26.00 ± 2.00	23.67 ± 1.53	10.00 ± 1.73	7.89 ± 2.42	28.45	<0.001	4.23
16-Mar	16.44 ± 1.33	17.33 ± 1.15	25.33 ± 1.15	24.33 ± 0.58	17.33 ± 4.04	7.67 ± 1.53	32.12	<0.001	3.89
23-Mar	15.89 ± 2.42	23.11 ± 3.18	26.33 ± 1.53	23.33 ± 1.53	19.00 ± 6.56	8.89 ± 2.03	18.76	<0.001	5.67
30-Mar	16.11 ± 2.67	18.44 ± 2.07	32.00 ± 4.58	23.67 ± 1.53	17.67 ± 3.06	9.33 ± 2.87	29.34	<0.001	4.98
6-Apr	8.56 ± 3.72	20.11 ± 2.32	17.00 ± 2.00	9.67 ± 1.53	4.67 ± 1.53	4.44 ± 3.36	35.78	<0.001	4.12
13-Apr	10.44 ± 2.70	22.00 ± 2.65	22.00 ± 1.00	10.00 ± 5.29	5.33 ± 0.58	4.11 ± 1.76	48.90	<0.001	3.87
20-Apr	12.67 ± 2.96	23.11 ± 2.85	16.00 ± 4.00	11.33 ± 4.51	5.33 ± 1.15	4.44 ± 2.70	32.45	<0.001	4.56
27-Apr	14.33 ± 1.53	23.22 ± 2.39	18.33 ± 2.52	10.00 ± 2.65	6.33 ± 2.52	4.33 ± 3.21	45.67	<0.001	3.78
4-May	16.11 ± 3.48	29.33 ± 2.00	29.33 ± 4.73	39.00 ± 9.54	32.00 ± 1.00	22.89 ± 4.82	22.34	<0.001	7.45
11-May	15.89 ± 5.11	27.33 ± 3.51	30.67 ± 7.57	44.67 ± 10.69	25.33 ± 4.04	23.78 ± 2.39	25.89	<0.001	8.12
18-May	16.44 ± 3.47	21.78 ± 3.80	22.33 ± 2.52	45.00 ± 1.00	34.67 ± 1.53	14.89 ± 3.18	98.45	<0.001	4.56
Overall	14.12 ± 4.23	21.89 ± 4.87	24.56 ± 5.12	25.34 ± 11.23	16.78 ± 9.45	10.23 ± 7.34	45.67	<0.001	3.45
F value	45.67						-	-	-
P value	< 0.001						-	-	-
LS.D	3.45						-	-	-

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

Foraging dynamics of honey bees in onion fields

The analysis of honey bee (*A. mellifera*) foraging activity in onion fields during the 2023&2024 season revealed highly significant and consistent temporal patterns, as comprehensively detailed in Figure 2. The data demonstrate highly significant diurnal variations ($P < 0.001$) across all monitoring dates, with distinct peak activity periods. Molasses extract and licorice extract consistently stimulated the highest foraging rates. Specifically, molasses reached its peak activity at 3 pm in both years (15.77 in 2023; 15.64 in 2024, bee/plant/m²), while licorice showed a strong performance particularly at 1 pm (13.10 in 2023; 13.64 in 2024, bee/plant/m²).

Beeswax comb extract and wormwood extract showed moderate foraging stimulation, significantly higher than the control groups but lower than the sugary/aromatic extracts. Both the Control (untreated) and Water groups exhibited the lowest foraging levels throughout the day, with activity often dropping to its lowest point at 1 pm (2.18 and 2.27 in 2023 and 2024, bee/plant/m², respectively), likely due to high ambient temperatures during the midday period. The patterns observed in 2023 were closely mirrored in 2024, suggesting that the stimulatory effect of these extracts is highly reproducible under varying environmental conditions.

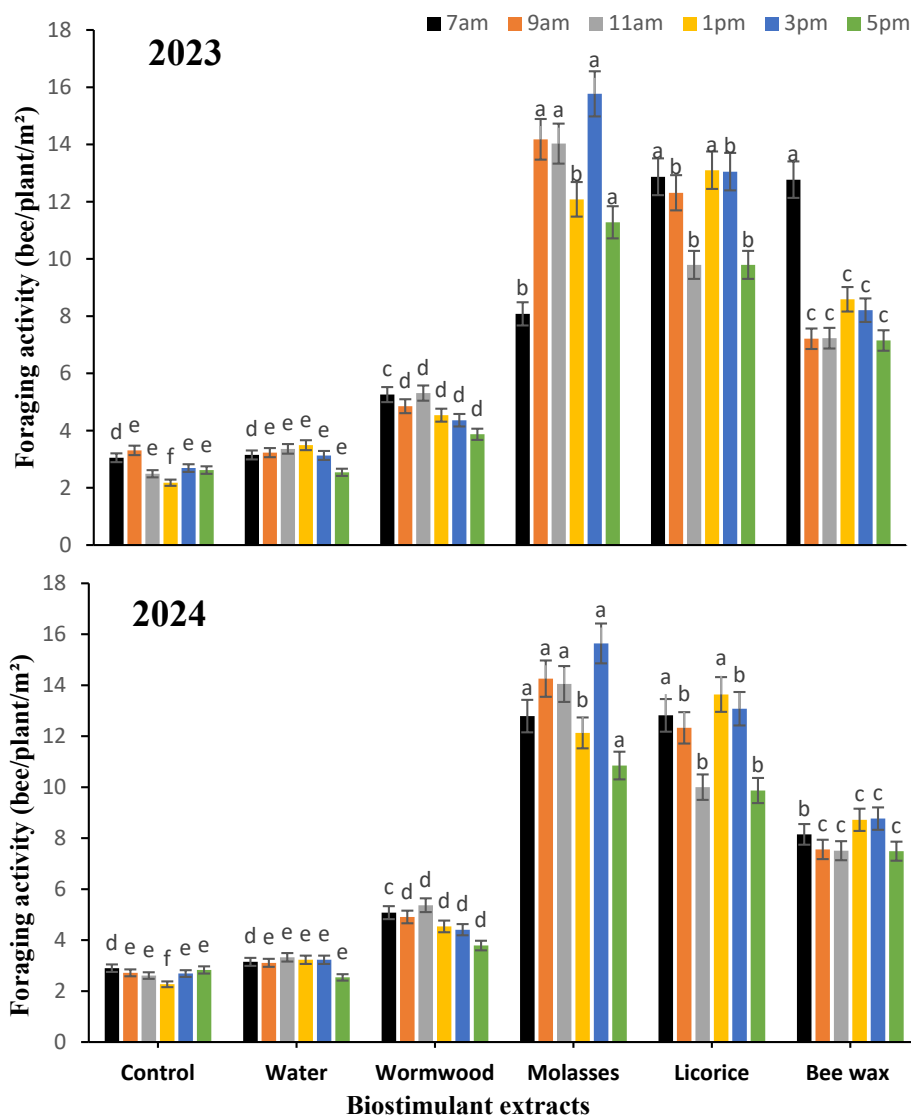


Figure-1. Foraging dynamics of *Apis mellifera* L. in onion fields (bee/plant/m²) during the 2023 and 2024 seasons in response to various natural extracts. Points represent the mean foraging rate at 2-hour intervals (7am, 9am, 11am, 1pm, 3pm and 5pm). Letters within intervals indicate statistically significant differences ($p < 0.05$).

Climatic Factors

Our observations, as shown in Table 3, indicate that temperature and humidity are the primary drivers of foraging activity. To quantify these

relationships, we performed Pearson correlation analysis between mean foraging activity (bees/colony/min) and the two main meteorological variables (temperature and relative humidity) across the study period. In fact, a strong positive

correlation with temperature and a negative correlation with humidity were observed. The high F-values and statistical significance ($P < 0.001$) across all sampling dates in Table-1, coupled with relatively low LSD values, confirm the robustness of these observed temporal and seasonal patterns.

In both seasons, a noticeable and steady increase in temperatures occurred from March through May, with May recording the highest values during the flowering period; during this time, the maximum temperature rose from 27.5°C in March to 37.5°C in May, while the mean temperature increased from 20.0°C in March to 29.9°C in May (sup. data). In contrast to the rising temperature trend, relative humidity showed a marked and steady decrease from March to May, dropping from 28.5% in March the highest level recorded to just 18.5% in May, which marks the lowest point of the season. However, the data reveal a clear inverse relationship between the two variables, as the significant decrease in relative humidity from March to May coincided directly with the steady rise in temperatures over the same period.

An analysis of weather stability reveals that the flowering period of the onion crop experienced consistently shifting conditions, transitioning from

a relatively moderate and humid character in March to a notably hot and dry character in May; this progression is reflected in the standard deviation values, which show that temperatures were most stable in March while humidity was most variable during that same month (with a standard deviation of ± 5.2), whereas May exhibited the most temperature fluctuation but the most stable humidity levels (with a standard deviation of ± 3.8).

Correlation coefficients (Table-3) between temperature and foraging activity were consistently high and significant ($r = +0.83-0.86$, $p < 0.01$), with temperature alone explaining 69–74% of the variation ($R^2 = 0.691-0.743$) a notably strong effect for field data. Humidity exhibited a clear inverse relationship ($r = -0.77$ to -0.81), likely due to associations with rain, increased nectar viscosity, or adverse flight conditions. Including humidity improved model fit only modestly (+5–8 percentage points), indicating that temperature is the dominant driver while humidity acts as a secondary modulator. Results were consistent across 2023 and 2024, suggesting biological robustness rather than year specific anomalies.

Table-3. Summary of correlation and regression parameters for honey bee foraging activity in relation to environmental factors (2023-2024) seasons.

Parameter	2023	2024	Combined
Correlation with Temperature (r)	+0.862**	+0.831**	+0.847**
Correlation with Humidity (r)	-0.814**	-0.769**	-0.792**
R ² (Temperature only)	0.743	0.691	0.717
R ² (Humidity only)	0.663	0.591	0.627
R ² (Multiple regression)	0.796	0.767	0.782
Adjusted R ²	0.781	0.749	0.765
F-value	52.34**	44.78**	48.92**
Standard Error	6.78	7.23	7.01

**Significant at $P < 0.01$

Impact of biostimulant extracts on onion seed yield quantity

The results in Table 4 clearly demonstrate that spraying onion crops with biostimulant extracts significantly enhanced all measured seed production parameters compared to the control and water spray treatments in the first year of application, 2023. The statistical analysis showed highly significant differences among treatments for scape weight, seed scape weight, yield per 9 m², 1000-seed weight, and estimated yield per hectare ($P < 0.0001$ in most cases), confirming that the enhancements were not due to random variation (LSD = 0.34 for seed scape).

As shown in Table-4, the old wax combs treatment yielded the highest performance across all parameters (scape weight: 7.87 g; seed scape weight: 4.07 g; 1000-seed weight: 5.33 g; yield/9 m²: 369.5 g; yield/ha.: 163.9 kg). Licorice root extract was the next most effective treatment, producing notable results, particularly in seed scape weight

(3.60 g) and yield/ha. (134.9 kg). Conversely, covered inflorescences (pollinator-excluded) resulted in the lowest productivity (55.5 kg/ha.), underscoring the essential role of honey bee foraging in onion seed production.

Statistical analysis of the data presented in Table 5 revealed that the foliar application of different biostimulant extracts had a highly significant effect ($P < 0.001$) on all measured parameters of onion seed production at the second year of application, 2024, as indicated by the high F-values and low P-values. Old beeswax comb extract exhibited superior performance, yielding the highest values across all parameters (scape weight: 8.03 \pm 0.21 g; seed/scape: 4.27 \pm 0.25 g; yield/9m²: 921.6 \pm 54.4; 1000-seed weight: 7.67 \pm 0.21 g; yield/ha.: 172.0 \pm 24.2 kg), and was statistically superior to other treatments.

Licorice extract ranked second (seed/scape: 3.93 \pm 0.15 g; yield/9m²: 849.6 \pm 33.0; yield/ha.:

158.6±14.7 kg), followed closely by molasses extract (scape weight: 6.53±0.42 g; seed/scape: 3.53±0.15g; yield/ha.: 142.5±14.7 kg), with both forming a statistically distinct high-performing category. The *Artemisia* extract treatment exhibited a moderate but statistically significant stimulatory effect on onion seed production, achieving a mean yield of 118.3 ± 14.7 kg/ha., along with scape weight of 6.30 ± 0.46 g and seed weight per scape of 2.93 ± 0.15 g; these values were consistently lower than those obtained with licorice and molasses treatments but higher than the control, reflecting a partial positive influence. In contrast, the control and water spray treatments

produced the lowest results among uncovered inflorescences, with yields of 94.08 ± 14.7 kg/ha. and 108.9 ± 25.4 kg/ha., respectively the modest difference between them, when considered relative to the LSD, indicates that applying water alone provides no significant advantage over the untreated control.

The most severe suppression occurred with inflorescence covering, resulting in the lowest values across all production parameters, including a mean yield of only 87.36 ± 29.3 kg/ha.

Table-4. Effect of biostimulant sprays as honey bee attractants on onion flower visitation and seed production parameters in 2023 season.

Treatment	Parameters of air dry weight (Mean ± SD)				
	Scape (g)	Seed scape (g)	9 sq. meter	1000 seeds of scape (g)	Kg/ha.
Control	4.33±0.45c	2.00±0.10d	430.8±19.8d	4.13±0.40c	80.43±8.97d
Water spray	4.67±0.45c	2.30±0.20cd	496.8±43.4cd	4.48±0.38bc	92.4±19.2cd
Wormwood (<i>Artemisia</i>)	4.99±0.34c	2.67±0.25c	576.0±54.7c	4.50±0.20bc	107.5±24.0c
Molass	6.17±0.25b	3.13±0.21b	676.8±44.4b	4.57±0.06bc	126.3±19.2b
Licorice	7.20±0.36a	3.60±0.10a	777.6±21.6a	4.90±0.10b	134.9±40.0b
Old wax combs	7.87±0.40a	4.07±0.15a	879.7±33.3a	5.33±0.45a	163.9±14.4a
Covered inflorescences	4.20±0.30c	1.40±0.2e	297.4±65.8e	4.13±0.15c	55.5±27.3e
F value	28.45	69.95	62.37	7.32	36.91
P value	<0.001	<0.0001	<0.001	<0.0001	<0.001
Tukey's HSD (0.05)	0.98	0.41	89.34	0.56	48.67

Means in the same column followed by the same letter do not differ significantly at the 5% level of probability according to Tukey's HSD test. P>0.05 considered non-significant, p<0.05 = * (significant) and p<0.01 = ** (high significant).

Table-5. Effect of biostimulant sprays as honey bee attractants on onion flower visitation and seed production parameters in 2024 season.

Treatment	Parameters of air dry weight (Mean ± SD)				
	Scape (g)	Seed scape (g)	9 sq. meter	1000 seeds/scape (g)	kg/ha.
Control	4.73 ± 0.47d	2.33 ± 0.15d	504.0 ± 33.0d	4.43 ± 0.25e	94.08 ± 14.7d
Water spray	5.20 ± 0.36cd	2.70 ± 0.26cd	583.2 ± 57.2cd	4.53 ± 0.45e	108.9 ± 25.4cd
Wormwood (<i>Artemisia</i>)	6.30 ± 0.46bc	2.93 ± 0.15c	633.6 ± 33.0c	5.83 ± 0.15d	118.3 ± 14.7c
Molasses	6.53 ± 0.42b	3.53 ± 0.15b	763.1 ± 33.2b	6.57 ± 0.21c	142.5 ± 14.7b
Licorice	7.23 ± 0.31ab	3.93 ± 0.15a	849.6 ± 33.0a	7.03 ± 0.15b	158.6 ± 14.7ab
Old wax combs	8.03 ± 0.21a	4.27 ± 0.25a	921.6 ± 54.4a	7.67 ± 0.21a	172.0 ± 24.2a
Covered inflorescences	4.33 ± 0.47d	2.17 ± 0.31d	468.0 ± 66.0d	5.03 ± 0.15e	87.36 ± 29.3d
F value	35.21	42.93	43.66	107.59	36.15
P value	<0.001	<0.0001	<0.0001	<0.0001	<0.0001
Tukey's HSD (0.05)	0.82	0.44	89.45	0.71	43.89

Means in the same column followed by the same letter do not differ significantly at the 5% level of probability according to Tukey's HSD test. P>0.05 considered non-significant, p<0.05 = * (significant) and p<0.01 = ** (high significant).

Impact of biostimulant extracts on onion seed yield quality

Sterility Percentage

The results showed a highly significant effect of all treatments on sterility percentage in both seasons (P < 0.001). The old wax comb treatment recorded the lowest sterility percentage (4.63% in 2023 and 6.43%

in 2024), indicating its effectiveness in attracting pollinators and improving pollination. indicated regarding the role of wax compounds in secreting bee-attracting substances. In contrast, the covered inflorescences treatment recorded the highest overall sterility rate (24.20% in 2023 and 27.27% in 2024) due to preventing pollinator access to the flowers, conclusively confirming the critical findings

discussed at length. The liquorice and molasses treatments also recorded low sterility values, attributed to their role in improving the plant's metabolic efficiency.

Number of Flowers per Plant

The effects of the treatments on flowering and sterility were profound. The old wax comb treatment resulted in the lowest sterility percentage ($4.63 \pm 0.60\%$) and the highest number of flowers per plant (786.33 ± 23.50), significantly outperforming all other treatments (Table-6). In contrast, the covered inflorescences treatment consistently showed the poorest performance, with the highest sterility rate ($24.20 \pm 9.95\%$).

Seed Weight (g)

All treatments had a highly significant effect on seed weight ($P < 0.001$). The old wax comb treatment ranked first with the highest seed weight (4.18 g in 2023 and 4.35 g in 2024), followed closely by the molasses treatment. This improvement is attributed to enhanced fruit set and the mobilization of

carbohydrates to the seeds, supporting the hypothesis of Reference regarding the role of organic treatments in enhancing the translocation of assimilates to the seeds. Again, the covered inflorescences treatment recorded the lowest seed weight (1.75 g in 2023 and 1.89 g in 2024) due to failed pollination and fruit set, confirming the fundamental conclusions.

Germination Percentage

The germination percentage followed a pattern similar to that of seed weight. The highest values were recorded under the old wax comb treatment (96.33% in 2023 and 95.33% in 2024) and the molasses treatment (93.67% in 2023 and 92.67% in 2024). This strong positive correlation between seed weight and germination vigor indicates that these treatments produced more vigorous and viable seeds, as reflected in the final germination percentage. Potential mechanisms underlying this integrated effect on seed quality were discussed. As expected, the covered inflorescences treatment resulted in the lowest germination percentage.

Table-6. Comprehensive statistical analysis (mean \pm SD) of flowering and production traits under different treatments during 2023 and 2024 season

Year	Treatment	Sterility (%)	Flowers/Plant	Seed Weight (g)	Germination (%)
2023	Control	$11.63 \pm 1.32 \text{ d}$	$373.33 \pm 42.03\text{d}$	$2.28 \pm 0.31 \text{ d}$	$84.33 \pm 2.52 \text{ d}$
	Water spray	$8.77 \pm 1.15 \text{ c}$	$539.67 \pm 77.98\text{bc}$	$2.75 \pm 0.28 \text{ c}$	$87.67 \pm 3.06 \text{ c}$
	Wormwood (<i>Artemisia</i>)	$12.20 \pm 2.48 \text{ d}$	$479.33 \pm 122.64 \text{ cd}$	$2.45 \pm 0.35 \text{ d}$	$83.00 \pm 4.36 \text{ d}$
	Licorice	$6.87 \pm 3.60 \text{ b}$	$559.67 \pm 85.01 \text{ b}$	$3.25 \pm 0.42 \text{ b}$	$90.33 \pm 3.51 \text{ b}$
	Molasses	$5.40 \pm 1.44 \text{ ab}$	$512.33 \pm 59.97 \text{ bc}$	$3.85 \pm 0.38 \text{ a}$	$93.67 \pm 2.52 \text{ ab}$
	Old wax comb	$4.63 \pm 0.60 \text{ a}$	$786.33 \pm 23.50 \text{ a}$	$4.18 \pm 0.29 \text{ a}$	$96.33 \pm 1.53 \text{ a}$
	Covered inflorescences	$24.20 \pm 9.95 \text{ e}$	$444.33 \pm 19.50 \text{ cd}$	$1.75 \pm 0.25 \text{ e}$	$72.33 \pm 5.51 \text{ e}$
	F value	25.84	22.67	38.45	28.93
	P value	<0.001	<0.001	<0.001	<0.001
Tukey's HSD (0.05)	3.98	48.67	0.44	4.23	
2024	Control	$13.38 \pm 1.82 \text{ d}$	$372.33 \pm 99.51 \text{ e}$	$2.34 \pm 0.25 \text{ e}$	$85.67 \pm 3.06 \text{ c}$
	Water spray	$15.43 \pm 0.40 \text{ e}$	$562.00 \pm 13.00 \text{ cd}$	$2.89 \pm 0.18 \text{ d}$	$82.33 \pm 2.52 \text{ cd}$
	Wormwood (<i>Artemisia</i>)	$14.93 \pm 4.60 \text{ de}$	$571.33 \pm 183.07 \text{ cd}$	$2.95 \pm 0.32 \text{ d}$	$83.67 \pm 4.04 \text{ c}$
	Licorice	$10.87 \pm 1.35 \text{ c}$	$553.00 \pm 10.54 \text{ d}$	$3.45 \pm 0.26 \text{ c}$	$88.33 \pm 2.52 \text{ b}$
	Molasses	$7.20 \pm 0.90 \text{ b}$	$600.00 \pm 42.33 \text{ c}$	$4.12 \pm 0.35 \text{ b}$	$92.67 \pm 3.06 \text{ a}$
	Old wax comb	$6.43 \pm 0.86 \text{ b}$	$706.33 \pm 2.52 \text{ b}$	$4.35 \pm 0.29 \text{ a}$	$95.33 \pm 2.08 \text{ a}$
	Covered inflorescences	$27.27 \pm 3.90 \text{ f}$	$802.33 \pm 29.55 \text{ a}$	$1.89 \pm 0.22 \text{ f}$	$75.67 \pm 4.04 \text{ d}$
	F value	38.75	25.43	45.67	32.89
	P value	<0.001	<0.001	<0.001	<0.001
Tukey's HSD (0.05)	3.56	52.34	0.41	4.67	

Means in the same column followed by the same letter do not differ significantly at the 5% level of probability according to Tukey's HSD test. $P > 0.05$ considered non-significant, $p < 0.05 = *$ (significant) and $p < 0.01 = **$ (high significant).

Impact of biostimulant extracts on onion seed yield increase and fertilization rate

The application of different natural extracts significantly increased onion seed yield and fertilization rate. The statistical analysis revealed a highly significant effect of the treatments, as indicated by an F-value of 3147 and a p-value of < 0.001 (Table-7). Molasses extract was the most effective treatment, resulting in the highest yield increase of $38.2\% \pm 3.5$ and the highest fertilization

rate of $84.5\% \pm 4.2$. This was followed by beeswax comb, which yielded a $28.1\% \pm 2.8$ increase and a $78.2\% \pm 3.8$ fertilization rate. The treatments of licorice and *Artemisia* (wormwood) showed moderate but significantly lower results, with yield increases of $19.3\% \pm 2.2$ and $8.4\% \pm 1.5$, and fertilization rates of $72.6\% \pm 3.5$ and $65.3\% \pm 3.1$, respectively. In contrast, the water (control) treatment not only failed to increase yield but resulted in a significant decrease of $-3.2\% \pm 1.2$,

accompanied by the lowest fertilization rate of $60.1\% \pm 2.9$. From the above results, we could conclude that the yield /ha. in the 2023 Season was old wax combs extract produced 163.9 ± 14.4 kg/ ha, more than doubling the control yield (80.43 ± 8.97 kg/ ha.), while in the 2024 Season, similar results were observed with old wax combs extract yielding 172.0 ± 24.2 kg/ha. compared to 94.08 ± 14.7 kg/ha. for control ($F = 36.15$, $P < 0.001$). On the other side the sterility rates of covered inflorescence exhibited significantly higher sterility rates in both seasons and the germination efficiency of old wax combs extract achieved the highest germination rates ($94.5 \pm 1.5\%$), while covered inflorescence had the lowest ($75.4 \pm 5.2\%$).

Table-7. Yield Impact after the different treatments and the percent of increasing and fertilization rate on onion seed.

Treatment	Yield Increase (%)	Fertilization Rate
Molasses	38.2 ± 3.5 a	84.5 ± 4.2 a
Bee wax comb	28.1 ± 2.8 b	78.2 ± 3.8 b
Licorice	19.3 ± 2.2 c	72.6 ± 3.5 c
Wormwood (<i>Artemisia</i>)	8.4 ± 1.5 d	65.3 ± 3.1 d
Water	-3.2 ± 1.2 e	60.1 ± 2.9 e
F value	3147	2876
P value	<0.001	<0.001
Tukey's HSD (0.05)	3.8	4.5

Means in the same column followed by the same letter do not differ significantly at the 5% level of probability according to Tukey's HSD test. $P > 0.05$ considered non-significant, $p < 0.05 = *$ (significant) and $p < 0.01 = **$ (high significant).

DISCUSSION

In this study, the observed bimodal diurnal foraging pattern, with peaks in late morning and early afternoon, aligns with established literature on *A. mellifera* behavior in onion fields. In fact, our findings are consistent with Yucel and Duman (2005), who reported peak foraging on onion between 11:00 and 12:00 hrs. Similarly, Mazeed and Marey (2018) recorded a peak of 60.33 bees/min at 11 am in Upper Egypt. The decline during early morning and late afternoon likely reflects suboptimal climatic conditions, such as lower temperatures and higher humidity. This is supported by Sihag and Khatkar (1999), who found a negative correlation between foraging activity and relative humidity.

Moreover, Divija and Kamala-Jayanthi (2022) similarly reported that weather conditions highly influence bee foraging activity. This pattern is likely driven by the interaction between floral nectar secretion rhythms and favorable microclimatic conditions, particularly rising temperatures and declining humidity, as previously reported. The significant seasonal increase in foraging activity from March to May in our study correlates with colony

growth cycles and improved climatic conditions, enhancing floral resource availability, as proved by Mabrouk and Mahbob (2017) and Amro (2021). This trend is biologically synchronized with the colony's growth cycle, as noted by Ulgezen et al. (2025), who stated that brood rearing activity intensifies during spring, thereby increasing the demand for forage.

Our diurnal and seasonal variation results align with those reported by Korichi et al. (2023), who noted that *A. mellifera* begins foraging in the morning and reaches peak activity between 11:00 and 16:00 h. This pattern can be attributed to environmental factors. Our data indicated a strong positive correlation between rising temperatures and increased foraging activity, while a negative correlation was observed with humidity, a relationship also supported by the observations of Divija and Kamala-Jayanthi, (2022) on the influence of environmental and genetic factors on pollination activity. The significant enhancement of *A. mellifera* foraging activity observed in response to molasses and licorice extracts (Figure 2) can be attributed to the synergistic effect of high carbohydrate concentrations and volatile aromatic profiles, which serve as potent olfactory cues and phagostimulants (Vanderplanck et al., 2014).

While foraging frequency in control and water-treated groups declined during the midday period (1 pm) likely a thermoregulatory response to peak ambient temperatures and low relative humidity characteristic of the Egyptian climate (Abou-Shaara, 2014) the stimulatory extracts maintained high recruitment levels, suggesting that chemical attraction successfully mitigated the inhibitory effects of environmental stressors. The moderate activity elicited by beeswax comb extract likely stems from the presence of nest-associated cuticular hydrocarbons that facilitate orientation (Noel et al., 2023), whereas the lower palatability of wormwood extract compared to saccharide-rich treatments may be due to the repellent nature of its bitter secondary metabolites. These findings suggest that integrating specific natural extracts can optimize colony foraging dynamics and pollination efficiency under challenging field conditions (Garrido et al., 2024).

Our findings also support the critical role of open pollination for optimal fruit set in onions, aligning with the observations of Seyad et al. (2004) and Soto et al. (2015), who reported significantly higher seed set in open-pollinated umbels compared to caged ones. Biostimulant treatments, particularly old wax comb and licorice extracts, substantially enhanced seed yield and quality parameters across both seasons, with old wax comb extract emerging as consistently superior (Paschapur et al. 2022).

The dramatic yield reductions under pollinator exclusion (covered inflorescences) unequivocally demonstrate the indispensable role of insect-mediated pollination in onion seed set, corroborating earlier exclusion studies that reported 70–80% lower yields in the absence of pollinators (Soto et al. 2023).

The superior performance of wax-derived extracts likely stems from volatile compounds that mimic natural bee attractants, thereby increasing visitation rates and pollination efficiency. Improvements in sterility percentage, flower number, seed weight, and germination under effective treatments reflect integrated benefits: enhanced pollinator attraction combined with potential physiological stimulation of carbohydrate translocation and seed filling (Monasterio et al. 2023).

Our finding powerfully validates the critical importance of open pollination for onion seed production. It aligns perfectly with previous research such as Seyad et al. (2004), who observed that seed yield per inflorescence was 2.4 times higher in the presence of pollinators, and Chandel et al. (2004), who reported that without insect visits, onions fail to produce quality seed, with induced bee pollination increasing seed yield by 2.5 times and dramatically improving germination. The fact that the covered treatment performed worse than the untreated control in many instances confirms that the improvements from the other treatments are due to their bioactive properties and not merely environmental modification. In this study, the high fertilization rates and yield increments associated with molasses and wax comb extracts further support their efficacy as sustainable pollination-enhancing agents.

Moreover, in line with recent studies (Soto et al. 2015, Pushpalatha et al. 2023, Korichi et al. 2023), the drastic reduction in yield and seed quality under the pollinator exclusion treatment definitively confirms the indispensable role of insect pollination, specifically by honey bees, for commercial onion seed production in this system. The strong positive correlation between seed weight and germination percentage indicates that effective pollination and biostimulant application not only increase yield but also enhance seed viability, a critical factor for agricultural productivity (Yucel and Duman 2005, Paschapur et al. 2022).

These integrated findings demonstrate that managing both pollinator activity and plant physiology is key to optimizing seed production in arid agroecosystems. In this study, this drastic reduction in yield aligns strongly with previous studies on insect pollination exclusion. Our results are confirmed by the findings of Korichi et al. (2023), who reported that the average seed weight from caged quadrates (0.09 g) was substantially lower than from open quadrates (4.14 g).

Furthermore, this observation is strongly supported by Yucel and Duman (2005), who reported that the seed yield per bulb was significantly higher in open plots (5.17 g/flower) than in caged plots (1.29 g/flower). Together, these studies underscore that the physical exclusion of pollinator insects severely limits seed set and ultimate productivity. Our study underscores the synergistic potential of combining honey bee pollination with targeted natural

biostimulants to optimize onion seed production in arid regions, offering practical strategies for improving yield stability and seed quality under field conditions.

Conclusion

Honey bee (*A. mellifera*) pollination proved essential for onion seed production in Egypt's New Valley, with pollinator exclusion drastically reducing yield and increasing sterility. Foliar application of natural biostimulant extracts particularly old beeswax comb and licorice significantly enhanced bee foraging activity, pollination efficiency, seed set, and yield parameters across two seasons. Old beeswax comb extract consistently outperformed other treatments, achieving the highest seed yield, lowest sterility, and superior germination.

Foraging patterns followed diurnal and seasonal trends, peaking under warmer, drier conditions from March to May. These extracts are proposed to act as bee attractants, emitting volatiles that mimic floral or pheromonal cues. Integrating managed honey bees with targeted biostimulant sprays provides a sustainable, field-ready strategy to improve onion seed quantity and quality, with broader applicability in arid, pollinator-dependent agroecosystems.

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Author contribution: NSO, MSM, AMA, SHS, and OMO help with planning, data gathering, methodological planning, data gathering, experimenting, and putting up a study. All authors read and approved the final manuscript.

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