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Influence of stimulating nutritional additives on *Apis mellifera L.* Colony performance metrics

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Abstract

Nutritional stress related to pollen scarcity is the major cause of honeybee colony collapse during winter in Egypt. It also affects the colonies' ability to build up in early spring. In this study, the effect of four stimulating nutritional additives: (Spirulina, Chlorella, Moringa, pollens, along a treatment comprising of their mixture) on wintering ability, colony development, foraging activity, and citrus honey yield was evaluated from November 2024 to April 2025 at the Faculty of Agriculture, Benha University, Egypt. Colonies treated with the algae (Spirulina, Chlorella and mixture) showed better wintering ability. Similarly, all developmental indicators (egg area, sealed worker brood area, stored pollen, and number of bees) of the algae-supplemented colonies increased compared with those of the control colonies, with the greatest improvement observed in the chlorella-fed colonies. Foraging activity also increased in the algae-fed colonies, reflecting their growth metrics. Ultimately, the citrus honey yield was highest in the algae-fed colonies, with the spirulina-fed colonies producing the most. Our results provide novel insights into the mechanism by which nutritional additives can be used to reduce nutritional stress associated with a lack of natural pollen supply, particularly when using algae (Spirulina, Chlorella), thereby improving colony performance and increasing honey production.

Keywords: *Apis mellifera*, Colony's productivity, Foraging activity, Stimulating nutrition, Wintering ability

INTRODUCTION

Honeybees and bumblebees play an important role in pollination services in many agricultural cropping systems (Najarpoor et al. 2025), pollinating ¾ of crops *e.g.,* many fruit, vegetable, seed, nut and oil crops, (Potts et al. 2010, Potts et al. 2016). Additionally, the conservation of managed bees is crucial, in monocultures (Jehlík et al. 2019). Moreover, these are important elements in preserving plant biodiversity and supporting natural habitats (Katumo et al. 2022, Bahgat 2023).

Unfortunately, recent declines in managed colonies have raised concerns, with losses reaching approximately 7.4 - 49% in Europe (Gray et al. 2020, Gray et al. 2023) and 62% in America between June 2024 to March 2025 (Nearman et al. 2025). This decline is due to several biological and environmental challenges, including environmental pollution, climate change, habitat loss, pathogens, parasites, and malnutrition (Güneşdoğdu et al. 2023).

Some flowering crops are important food resources for honeybees (Lau et al. 2023), providing nectar (main source of carbohydrate) and pollen (source of protein, vitamins, fats, and minerals) (Brodschneider & Crailsheim 2010, Frias et al. 2016). However, many of the larger cultivated lands surrounding the apiaries may not meet the nutritional needs of those colonies (Satta et al. 2024). Nutritional stress, especially reduced protein intake, is a major factor affecting honeybee health. (Jang et al. 2022). It also weakens immunity and makes colonies more susceptible to disease (Wheeler & Robinson 2014, Branchiccela et al. 2019, Ewert et al. 2025). Furthermore, malnutrition may shorten the lifespan of bees, reduce foraging activity, and ultimately impact the colony's productivity (Sharaf El-Din et al. 2025).

Brood rearing often picks up speed from early spring until August in temperate countries like Egypt, when nectar and pollen are more readily available. Thereafter, unless protein feed is given, brood production decreases by late summer and virtually stops by winter (Knoll et al. 2020). The Egyptian agricultural environment is short on the floral resources bees need in early spring, so it is necessary to provide stimulant feeds to help colonies build up in preparation for the citrus season.

To compensate for nutritional deficiencies, beekeepers in Egypt administer supplemental feed during periods of floral dearth (winter and early spring) to support the nutritional needs of their colonies (Cengiz 2018, Underwood et al. 2019, Noordyke & Ellis 2021), for example, pollen substitute or supplement patties to supplement the colony diet. It is important to choose nutritional supplements that closely mimic the nutritional value of natural pollens to ensure the best results for bee colonies, including palatability for diet consumption and benefits to bees' health (Ghramh & Khan 2023). Beekeepers currently provide these supplements using a wide range of feeding techniques, the most common form being supplement patties, either whey, brewer's yeasts or soybean meals (DeGrandi-Hoffman et al. 2008). They may also use nutrients in dry powder (*e.g.,* chickpea flour, maize flour, sorghum flour, wheat flour) form outside the hives (Ghramh & Khan 2023, Noordyke & Ellis 2021) or mixed with sugar syrup (Jehlík et al. 2019, Sharaf El-Din et al. 2025).

Incorporating functional feed additives into bee diets is a promising approach to address nutritional deficiencies in bee colonies, enhance immune responses, and reduce stress (Ewert et al. 2025). Recently, microalgae (such as spirulina and chlorella) have gained popularity as a beneficial feed ingredient for bees due to their richness in essential macronutrients (proteins, lipids), micronutrients (minerals, vitamins), and antioxidants (Nichols & Ricigliano 2022, Ricigliano 2020, Ricigliano & Simone-Finstrom 2020).

Also, leaves *Moringa oleifera* contains significant amount of several important nutrients (protein 21.52 - 22.90% and lipds 7.94 - 9.11%), vitamins A, E and C and antioxidants (Mansour et al. 2016, Kashyap et al., 2022). These feed ingredients, microalgae (Nichols & Ricigliano 2022) and *M. oleifera* (Ali & Khalil 2017, El-Bahnasy et al. 2017) added to sugar syrup or patties. These additives provide essential nutrients, especially during pollen shortages, to boost bee immunity leads to increased expression of antimicrobial peptide genes (Ewert et al. 2025), total lipids in abdomen and vitellogenin (Ricigliano & Simone-Finstrom 2020, Ricigliano et al. 2021), brood production because it supports the development of the hypopharyengeal glands, which secrete royal jelly as a food for the larvae (Ricigliano et al. 2021, McMenamin et al. 2023), and improve colony productivity.

During winter, honeybees rely on stored honey and bee bread collected during the previous flowering period. However, this food supply may sometimes be insufficient. To compensate for this nutritional deficiency, beekeepers provide their colonies with nutritional supplements in the form of sugar solution or pollen substitutes (Bocquet & Tosi 2022, Elgebaly et al. 2025, Tunç et al. 2020). Proteinaceous feed additives in sugar solution may be a simple and promising strategy to compensate for this nutritional deficiency and to stimulate colonies to rapidly build up and prepare for the early spring flow season. They are also essential for colonies to produce drones, which colonies need (before the flow season) to mate with virgin queens (Mashal et al. 2023).

During periods of pollen deficiency in Egypt, honeybee colony loss rates reached of 35.5% and 38.8% during the period from September to March in 2011/2012 and 2012/2013, respectively (Moustafa et al. 2014), and 24.3% in 2019/2020 (Gray et al. 2023). The health of honeybee colonies (brood area, number of adult bees, and honey stores) are also affected by pollen shortages (Requier et al. 2017, Tawfik et al. 2020). Several studies have used these feed additives in patty form to feed bee colonies, but only one used chlorella (Jehlík et al. 2019), and another evaluated moringa (Ali & Khalil 2017) for their use in addition to sugar syrup. None of these studies has discussed the use of these feed additives to stimulate colony performance and foraging activity during winter and early spring, or their effect on foraging activity. Therefore, this study aimed to investigate the effect of different stimulating nutritional additives (Spirulina, Chlorella, Moringa, Pollen alone and in their mixture form) with sugar syrups for 5 months through winter and early spring in field conditions on wintering ability, colony development (egg area, brood rearing, number of combs and worker bee population), stored pollen area, foraging activity and honey production.

MATERIAL AND METHODS

Tested materials (Nutritional additives)

The algae powder (*Chlorella vulgaris* and *Spirulina platensis*) and moringa leaf powder (*Moringa oleifera*) were obtained from the National Research Center, Dokki, Giza, Egypt. Pollen grains (mostly from clover and maize) were collected by front wooden traps attached to beehives at the apiary at the Faculty of Agriculture, Benha University, Egypt, from June to August in the year preceding the experiment (2023).

Honeybee colonies

The honeybee, *A. mellifera carnica* was used in the experiment. In the apiary at the Faculty of Agriculture in Moshtohor, Benha University, Qalyoubia Governorate, Egypt (Elevation 52 feet, Latitude 30.3527° N, Longitude 31.2209° E), honeybee colonies were maintained. Newly mated sister queens led all colonies, which were nearly similar in strength. Three combs of sealed brood and two combs of honey and bee bread made up each colony's five combs, covered with bees. Upon examination, there were no indications of honeybee illnesses in these colonies. Additionally, they were treated with Mitac 20% (acaricide) and essential oils (peppermint, camphor, and garlic) at a 1:1 ratio, using cardboard soaked in the mixture to suppress Varroa mites. After that, the bees were kept according to conventional beekeeping practices.

Experimental design

Eighteen honeybee colonies with the above description, divided into six experimental groups, each containing three colonies as replicates. The first group served as a control and was fed only sugar syrup (sugar and water; 1:1), while the other groups received feed additives in powder form added to syrup, the second group fed with chlorella powder, third group was fed with spirulina powder, fourth group was fed with moringa leaf powder, fifth group was fed with pollen powder and sixth group was fed with a mix of all feed additives (Spirulina, Chlorella, Moringa, Pollen).

The studies were carried out from November 2024 to April 2025. To evaluate the effect of some protein feed additives on bee wintering ability, colony development, foraging activity, and citrus honey yield. Control colonies were fed sugar syrup only (1 L/colony) once a week. The feed additives (spirulina, chlorella, moringa, pollen, and their mixture) were added to the sugar solution at a dose of 10 grams per liter (30 grams per treatment group per week) once a week. In our study, we used equal doses of the tested materials: 10 grams of each nutritional additive. Given that the local Egyptian environment relies on monoculture farming, we collected pollen from the same environment to simulate the conditions faced by managed bee colonies in the wild.

Measurement of colony parameters

Wintering ability (WA%)

To determine the WA of bees, the number of combs covered with worker bees of each colony were determined in November 2024 (autumn) and in April 2025 (spring). The equation shown below, described by Cengiz & Erdogan (2017) and Guler et al. (2018), was used to determine the wintering ability (WA).

$$WA\ (\%) = \frac{No. combs\ covered\ with\ bees\ in\ spring}{No. combs\ covered\ with\ bees\ in\ autumn} \times 100$$

Colony development (egg area, brood rearing, number of combs and bee population), and stored pollen area

Egg area, sealed brood area and stored pollen (bee bread)

The measurements were performed 42 days after application of feed additives (27 November) and then every 13 days thereafter using a standard Langstroth frame divided into inch^2 square grids (Jeffree 1958, Büchler et al. 2013). The frame was positioned above the combs, and the dimensions of the eggs, sealed brood, and bee bread were measured.

Number of bees

Monthly, the honeybee population was assessed by visually counting adult bees on each fully occupied side of the combs within the colonies (Guzman-Novoa et al. 2024). Subsequently, the number of adult bees in the colony was then determined by multiplying the total values (previously estimated at 2,000 bees per fully covered side of the frame (standard Langstroth frame 19×9.13×17.64 inch) according to Guzman-Novoa et al. (2024), Kim et al. (2024) by the number of frames fully covered with bees on both sides (Guler et al. 2018).

Foraging activity

During the period preceding the citrus honey season in Egypt. Over eight weeks in February and March 2025, foraging activity was monitored by visually observing hives twice a week to count the number of forager bees leaving and returning to the hive, with or without pollen. Observations were conducted for 5 minutes between 8:00 and 10:00 a.m., as described by Islam et al. (2024a).

Honey yield

The amount of citrus honey produced for each treatment group was estimated by collecting the combs containing honey and weighing them before and after extraction to obtain the amount of honey (Ghazala & Nowar 2013).

Statistical analysis

Using SPSS, version 27 (IBM Corp., Released 2013), two-way ANOVA was executed to compare the effects of feed additives on colonies' bee bread area, brood area, population density of workers, and foraging activity. Also, use one-way ANOVA to compare its effects on wintering ability and citrus honey production. The analysis was conducted under a completely randomized design, as detailed by Steel et al. (1997). For multiple comparisons, the Duncan test was used, with a significance level of $p < 0.05$.

RESULTS

Wintering Ability (%)

Wintering ability was affected ($p < 0.05$) by types of proteinaceous feed additives to colonies (Figure 1). Colonies treated with protein additives outperformed untreated control colonies in their overwintering ability, and ranged between 140.00±0.00, 140.00±0.00, 126.67±6.67, 126.67±6.67, and 133.33±6.67% in colonies supplemented with spirulina, chlorella, moringa, pollen, and mix., respectively. It was 53.33±6.67% in control. The average number of combs covered with bees at the beginning of spring was (7±0.00, 7±0.00, 6.33±0.33, 6.33±0.33, 6.67±0.33 and 2.67±0.33 comb/colony) in colonies supplemented with spirulina, chlorella, moringa, pollen, mix., and control, respectively.

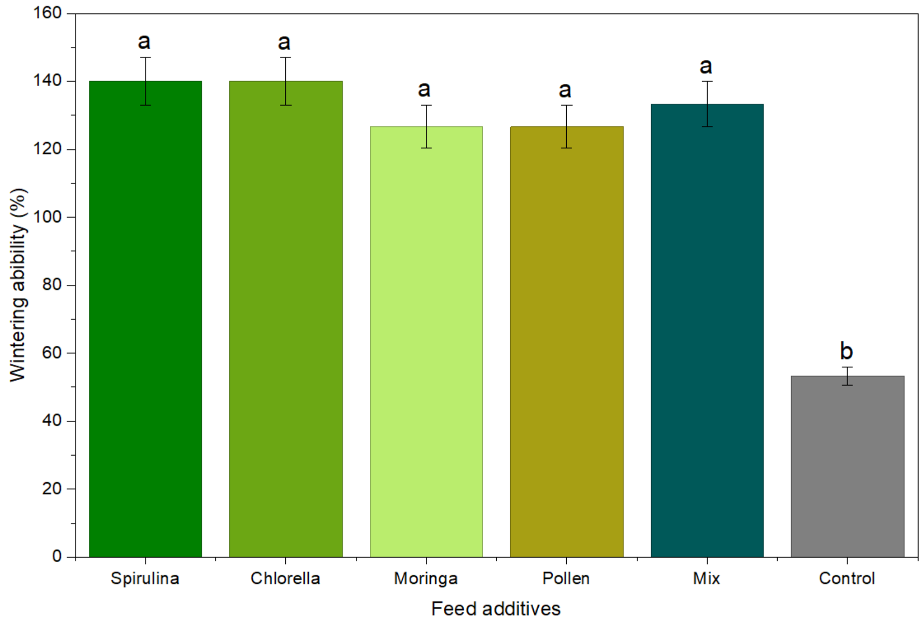

Figure 1. Effect of nutritional additives on the wintering ability (%) of honeybee colonies.

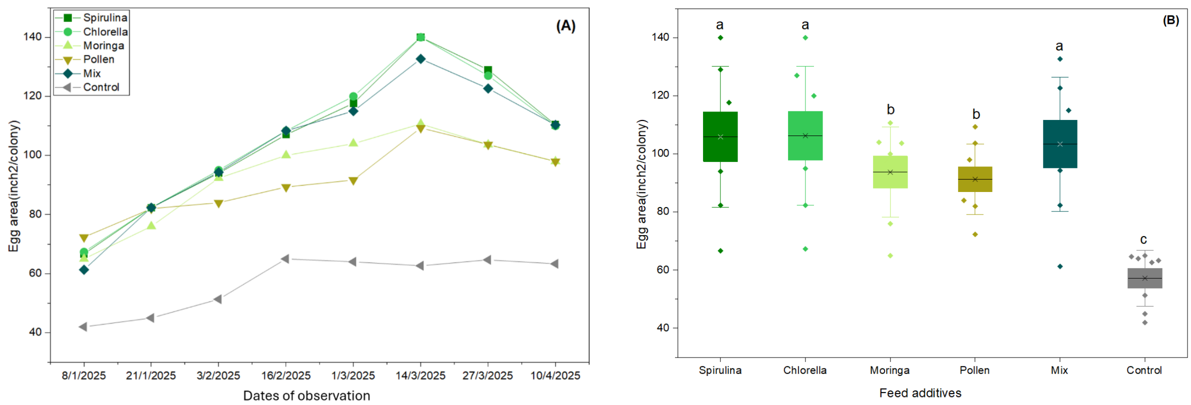

Figure 2. Effect of tested nutritional additives on egg area (inch^2/colony) in honeybee colonies. A, Pattern of change in egg area in treated colonies during the experiment. B, Total means of egg area.

Colony development

Weekly supplementation of honeybee colonies during the dearth period (from November 2024 to April 2025) with some nutritional additives revealed a significant increase in the developmental parameters of the colonies (egg, sealed brood, bee bread areas and number of bees) compared to control colonies ($p < 0.05$; Figures 2, 3, 4, and 5).

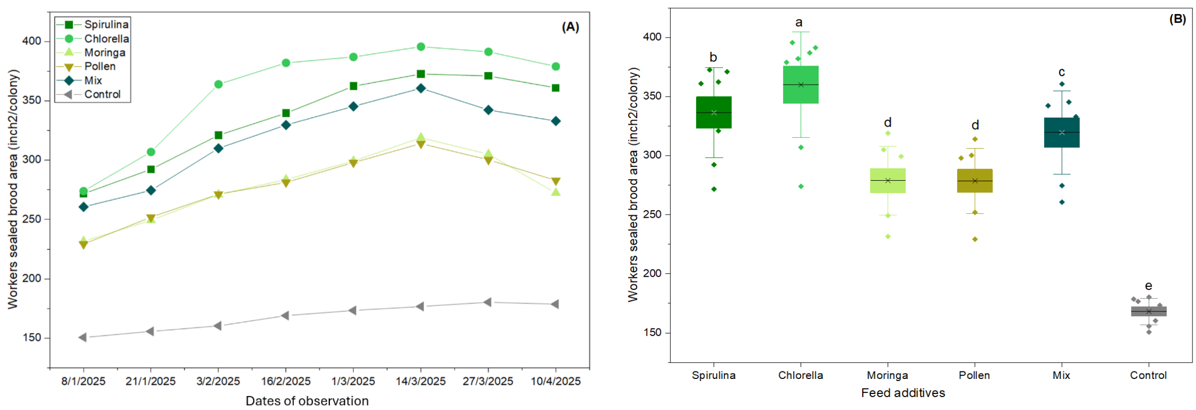

Figure 3. Effect of tested nutritional additives on workers sealed brood area (inch^2/colony) in honeybee colonies. A, Pattern of change in workers' sealed brood area. B, Total means of workers sealed brood area.

The overall average increase in egg area was 1.85, 1.86, 1.64, 1.6, and 1.81-fold in colonies supplemented with spirulina, chlorella, moringa pollen, and their mixtures, respectively, compared to control colonies with an overall average egg area of 57.25±2.71 inch2/colony (Figure 2B). While the overall average increase in sealed brood area was 2, 2.14, 1.66, 1.66, and 1.9-fold in colonies supplemented with spirulina, chlorella, moringa pollen and their mixtures, respectively, compared to control colonies, with an overall average sealed brood area of 168.08±2.54 inch^2/colony, (Figure-3B). The best results were observed from mid-March to the end of the experiment in both egg and sealed brood areas (Figure 2A and 3A).

Additionally, bee populations in the supplemented colonies with spirulina, chlorella, moringa pollen, and a mix of all of them, increased by 2.1, 2.1, 1.81, 1.78, and 2-fold, respectively, compared to the control colonies (Figure 4B).

On the other hand, the area of bee bread in control colonies was 32.5±2.90 inch²/colony, and this was increased in colonies treated with spirulina, chlorella, moringa, pollen, and a mixture of all of them, were 69.54±2.18, 75.46±3.83, 68.88±3.94, 58.21±2.77, 61.17±2.95 inch²/colony, respectively ($p < 0.05$; Figure-5B). Colonies during March recorded the highest significant average bread area ($p < 0.05$; Figure-5A). While, the colonies fed chlorella showed the highest significant improvement, recording the highest average bread area by mean 75.46±3.83 inch²/colony ($p < 0.05$; Figure 5B).

Also, regarding the developmental pattern of colonies during the experimental period, an increase in all developmental parameters was observed in the supplemented colonies with the nutritional additives compared to the control colonies. Spirulina, chlorella, and the combination were the most effective supplements in supporting colony development during the experiment. These indicators also increased during late February and March, 2025 (Figures 2A, 3A, 4A and 5A).

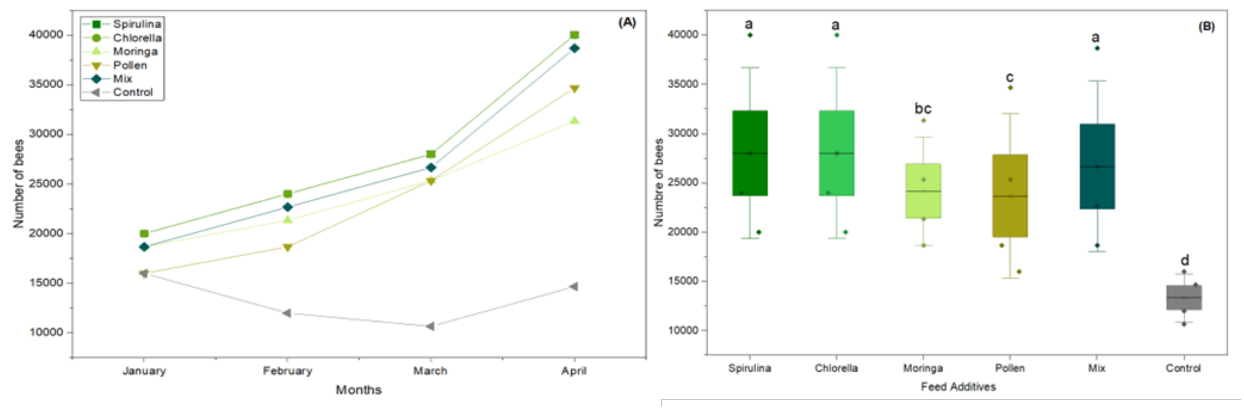

Figure 4. Effect of some nutritional additives on the number of bees in honeybee colonies. A, Pattern of change in the number of bees in treated colonies during the experiment. B, Total means of the number of bees.

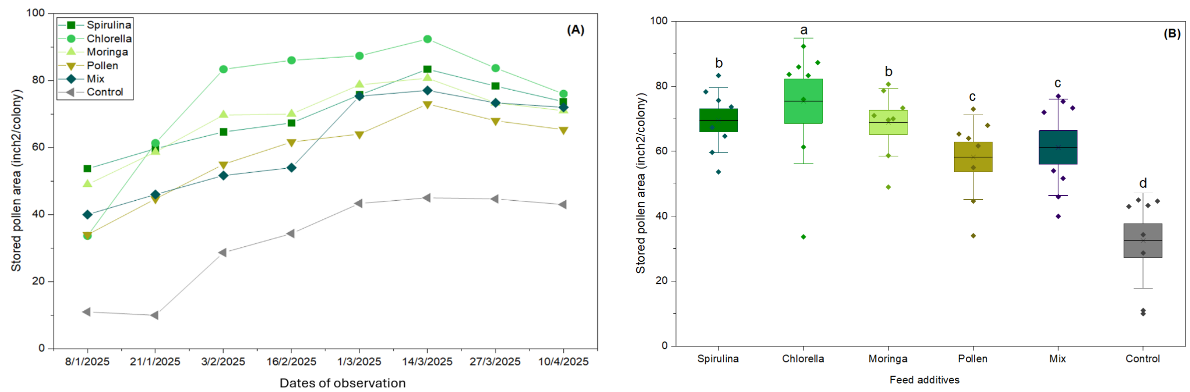

Figure 5. Effect of some nutritional additives on pollen area (inch^2/colony) in honeybee colonies. A, Pattern of change in pollen area in treated colonies during the experiment. B, Total means of stored pollen area.

Foraging activity

To investigate the effect of tested nutritional additives on foraging activity in honeybee colonies, we counted bees leaving and returning to their hives, and found that colonies supplied with nutritional additives had greater foraging activity compared to control bees ($P < 0.05$; Figures 6, 7, and 8).

Colonies fed with the mixture, spirulina, and chlorella demonstrated the highest average of outgoing bees (113.81±2.70, 113.35±2.83, and 113.13±2.66, respectively) over the eight-week period, followed by those fed moringa (85.25±3.33) and pollen (84.29±3.53), while the control colonies exhibited the lowest average of outgoing bees (65.35±3.14) (Figure 6B).

Regarding foraging activity pattern lines, the mean outgoing bee count was highest in week 8 (133.11±2.93), with colonies fed spirulina, chlorella, and the mixture performing best with means of 147.83±1.19, 146.00±1.61 and 147.67±1.23, respectively. This was followed by weeks 7 (120.67±2.86) and 6 (106.56±2.85), with colonies fed spirulina, chlorella, and the mixture showing the highest means, while the lowest mean was in week 1 (74.39±3.50) (Figure 6A).

For bees returning to their hives, the eighth week (168.89±4.80) had the largest average number of bees returning to their hives without pollen, followed by weeks 7 (158.14±5.03) and 6 (139.53±4.49). The first week had the lowest average number of bees returning without pollen (107.08±3.68) (Figure 8A and B). Week 5 had the highest mean number of pollen-carrying bees (158.28±5.61), followed by week 4 (151.42±5.53), while the first week had the lowest (140.69±5.57) (Figure 7A and B).

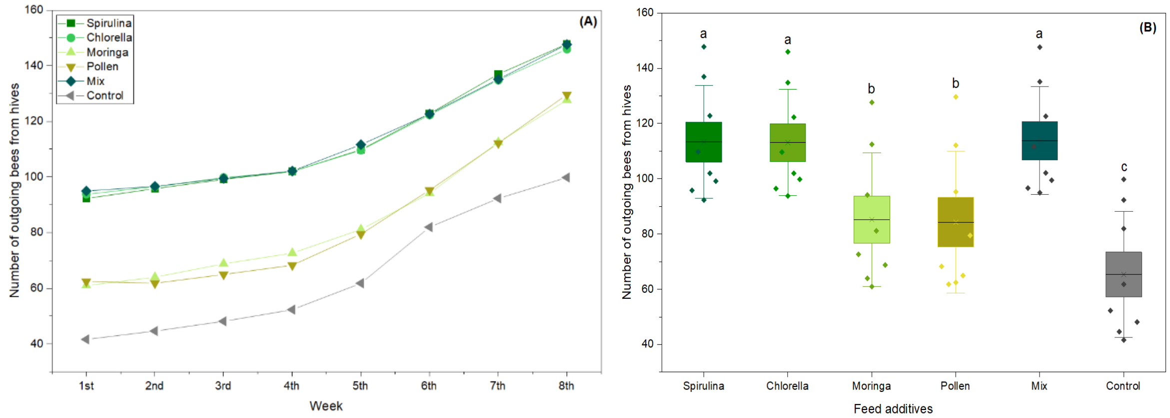

Figure 6. Effect of tested nutritional additives on outgoing foragers from their hives. A, Pattern lines of change in the number of outgoing foragers in treated colonies over the period of eight weeks. B, Total means the number of outgoing foragers.

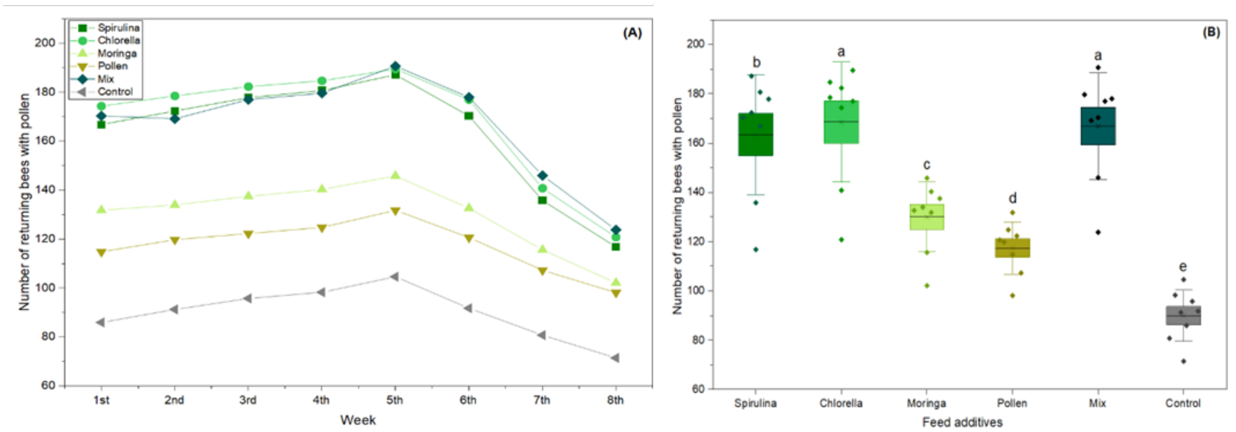

Figure 7. Effect of tested nutritional additives on incoming foragers with pollen to their hives. A, Pattern lines of change in the number of incoming foragers with pollen in treated colonies during the experiment. B, Total means the number of incoming foragers with pollen.

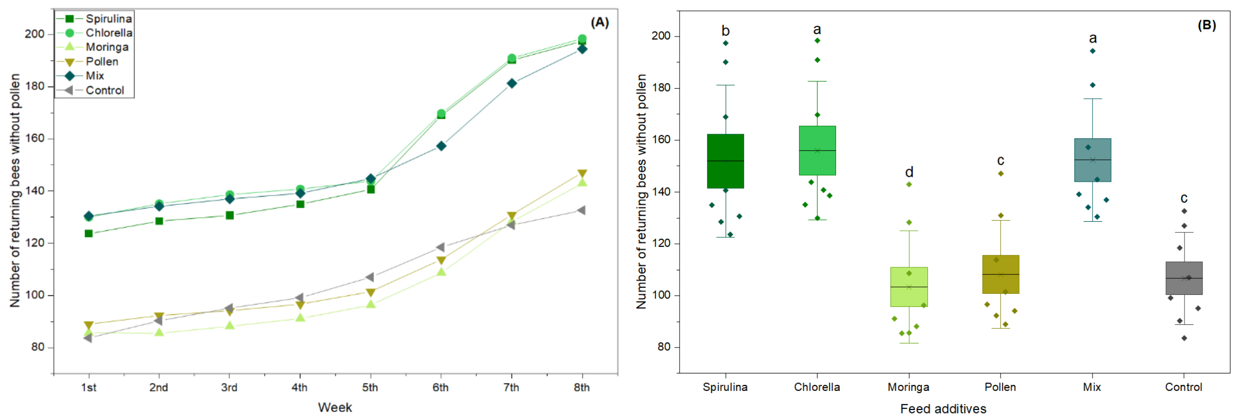

Figure 8. Effect of some nutritional additives on incoming foragers without pollen to their hives. A, Pattern lines of change in the number of incoming foragers without pollen in treated colonies during the experiment. B, Total means the number of incoming foragers without pollen.

Impact of feed additives on honey yield

Citrus honey was harvested in mid-April. The average honey yield was significantly affected by feed additives for colonies ($P < 0.05$; Figure 9). Colonies supplied with feed additives produced significantly higher honey production than control colonies (2.89±0.15kg/colony) by 94.18, 80.62, 24.22, 28.72, and 66.44% in colonies treated with spirulina, chlorella, moringa, pollen, and a mixture of all of them, respectively.

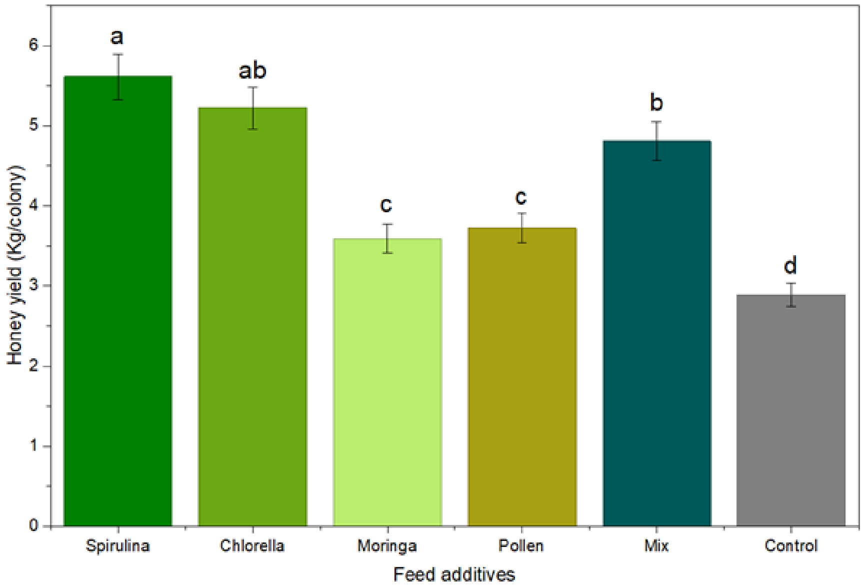

Figure 9. The total means of citrus honey yield from honeybee colonies fed with some nutritional additives during dearth period.

DISCUSSION

Using feed-protein powder in sugar syrup is a simple strategy for beekeepers to revitalize their colonies before flowering seasons (Sharaf El-Din et al. 2025). It also improves and accelerates the bees' consumption of feed-protein (Jehlík et al. 2019). Monoculture farming harms honey bees primarily through poor nutrition, as a single crop diet lacks essential amino acids, lipids, and vitamins (Clair et al. 2020, Alarcón et al. 2026). Since honeybees cannot synthesize arginine, histidine, lysine, tryptophan, phenylalanine, methionine, threonine, leucine, isoleucine, and valine, these amino acids must be obtained from their diet (De Groot 1953). The essential amino acids found in spirulina and chlorella have been found to be equal to or greater than those found in pollen (Jehlík et al. 2019, Ricigliano & Simone-Finstrom 2020).

The ability of bees to adapt to winter was higher in colonies treated with algae (spirulina, chlorella and mixtures). This is due to their high levels of protein, amino acids, and lipids, which are essential for honeybees and are greatly reduced in winter and during periods of scarcity when the natural pollen supply is low. This was followed by pollen and then moringa, both of which performed better than the control colonies, which lost many bees during the winter due to a lack of protein. To explain this, studies have shown that autumn protein feeding increases honeybees' body fat and protein stores (Irandoust & Ebadi 2013, Shumkova et al. 2017), increasing their capacity to endure the winter. Accordingly, some studies have shown that diets containing *Arthrospira platensis* and *Chlorella vulgaris* have led to a significant increase in the lipid content of fatty bodies (Jang et al. 2022, Ibrahim & Ayoub 2025, Ricigliano & Simone-Finstrom 2020). Also, algae (spirulina and chlorella) provide essential nutrients to support brood production by supplying larvae with feed from the HPG (Jehlík et al. 2019, Ricigliano & Simone-Finstrom 2020), thereby increasing the population of worker bees and enhancing the colonies' ability to withstand winter stress. Furthermore, spirulina extends the lifespan of worker bees through increased vitellogenin transcript levels (a protein associated with longevity and immunity) (Jehlík et al. 2019, Ricigliano & Simone-Finstrom 2020, Dostálková et al. 2022). Additionally, in our study, the control group fed sugar syrup had the lowest wintering ability at 66.67% (Figure 1). A study supporting our findings found that colonies fed sugar syrup had the lowest wintering ability (51.07%), according to Topal et al. (2022). Supplemental winter feeding for 18 weeks (November to March) was found to enhance colony development and health during the winter and lower colony losses in another study (Tawfik et al. 2020).

In terms of the growth and development of colonies, the availability of nutrients is crucial. Numerous previous studies have shown that protein supplements are essential for honeybees, as they meet their protein and amino acid requirements (Begum et al. 2023, Brodschneider & Crailsheim 2010, DeGrandi-Hoffman et al. 2010). In this regard, previous studies have shown that moringa is rich in nutrients, including protein, carbohydrates, dietary fiber, and fats, as well as vitamin C (Islam et al. 2024b, Moyo et al. 2011, Nathaniel et al. 2020). Algae (*Chlorella vulgaris* and *Spirulina* (=*Arthrospira*) *platensis*) also provide many important nutrients for honeybees (Ewert et al. 2025, Nichols & Ricigliano 2022), making them a sustainable and high-quality source of protein. its providing high-quality protein, essential amino acids, lipids, vitamins, and minerals, which contribute significantly to promoting the growth of honeybee colonies, as they are a sustainable and high-quality source of protein, stimulating brood rearing and improving nurse bee function by enhancing the development of the hypopharyngeal gland (Dostálková et al. 2022, Jang et al. 2022, Jehlík et al. 2019, Nichols & Ricigliano 2022, Ricigliano & Simone-Finstrom 2020).

Also, these protein supplements play a major role in the hypopharyngeal glands' development (Al-Ghamdi et al. 2011, Begum et al. 2023, DeGrandi-Hoffman et al. 2010, El Ghabawy et al. 2022, Omar et al. 2017), which is necessary for the secretion of royal jelly as a food for the queen and young worker larvae in the honeybee colony, which later represents the colony strength. In our study, there were significant differences for both the egg, sealed brood, and bee bread areas and bee population compared to control colonies (Figures 2, 3, 4, and 5), indicating that the increase in these developmental parameters was in response to feed additives especially in colonies fed spirulina, chlorella, and mixtures. This is consistent with multiple studies showing that colonies fed protein diets typically have larger brood areas and more workers than those fed sugar syrup alone (El Ghabawy et al. 2022, Güneşdoğdu et al. 2025, Hoover et al. 2022, Kumar & Agrawal 2014). Furthermore, protein supplements increased the daily rate of queen egg laying and the sealed brood area of workers (Ghazala & Nowar 2013, Fèvre & Dearden 2024). Additionally, a previous study reported that chlorella has positive effects on bee colony growth (Jehlík et al. 2019).

Another study by McMenamin et al. (2023) demonstrated that feeding commercial honeybee colonies an artificial diet containing 25% spirulina improved brood production compared to an unfed control group. Moreover, our results disagree with a study by Ali et al. (2017) which found that colonies fed a moringa supplement did not produce more brood compared to the control, we believe this is due to the higher concentration used in this study (60g moringa leaf powder extracted in 500ml water/1L honey 80%), while in our study only 10g/1L sugar solution was used. Additionally, the two studies differed in the timing of application, so this point warrants further investigation to determine the optimal concentration of moringa leaf powder. Also, colonies supplemented with the nutritional additives produced the highest number of worker bees. Undoubtedly, this is a response to the nutritional additives, which supported the health and immunity of the colonies and produced large brood areas, ultimately leading to a large population of worker bees. Ullah et al. (2021) found results that support ours.

In the same trend, foraging efforts increased in bee colonies supplemented with nutritional additives compared to control colonies (Figures 6, 7, and 8) especially in colonies fed spirulina, chlorella, and mixtures. Numerous studies confirm the hypothesis that the carbohydrates bees obtain from nectar or sugar syrup (are an essential source of energy), which are rapidly oxidized to provide energy for their flight muscles, are the crucial factor influencing foraging activity (Ansaloni et al. 2025, Brodschneider & Crailsheim 2010, Kunieda et al. 2006). However, for these flight muscles to develop, they require proteins and amino acids, which are essential for their growth (Stephen & Rehan 2026). Therefore, protein supplements enhance the bees' ability to fly longer distances. In a study by Ricigliano & Simone-Finstrom (2020), bees fed spirulina had higher thorax weights than those fed sucrose. Furthermore, increasing the egg-laying area in treated colonies can increase the foraging rate of large bees to ensure adequate feed supply for the larvae hatching from these eggs (Al-Tikrity 1972, Eckert 1994, Gąbka 2014, Tsuruda & Page 2009), as foraging behavior is influenced by the presence of brood pheromones and young larvae within the hive (Pankiw et al. 1998).

Additionally, the findings of several studies (Avni et al. 2009, Delaplane et al. 2013, Güneşdoğdu et al. 2025, Ullah et al. 2021, Wright et al. 2018) are consistent with our findings, indicating that the number of forager bees increased in colonies fed protein diets compared to those not fed protein. This suggests that protein availability is important in regulating bee energy levels and stimulating foraging efforts. Similarly, in a study conducted by Sharaf El-Din et al. (2025), colonies fed sugar syrup supplemented with 2% tuna extract as a protein additive showed increased foraging activity, which was reflected in the amount of honey, sealed brood area, bee bread, and overall colony health.

Regarding honey yield, this study confirms the findings of Islam et al. (2020), Ullah et al. (2021), and Elwakeil et al. (2025), who observed that supplying honeybee colonies with protein additives increased honey production compared with unfed control colonies. Additionally, Güneşdoğdu et al. (2025) reported that the colonies fed with Diet I and Diet II, which contain the pollen and spirulina, respectively, yielded the highest levels of honey production compared to unfed colonies. This superiority in honey production in colonies supplemented with protein additives resulted from a larger population of adult bees collecting more nectar from citrus trees, which was correlated with a higher rate of worker brood rearing in those colonies. In general, honey production increases in colonies supplemented with algal products (Nichols & Ricigliano et al. 2022), with honey production increasing by 28.8% when colonies were fed a spirulina patty (Toderaş et al. 2017) and by 12.1% in colonies fed chlorella with sugar syrup (Eremia et al. 2021).

On the other hand, Ali and Khalil (2017) found that colonies fed a moringa leaf extract had fewer honeycombs than the control colonies. Overall, the supplementation of bee colonies with the tested nutritional additives (Spirulina, Chlorella, Moringa and Pollen) improved their overwintering capacity, development of colonies (egg area, workers sealed brood area, stored pollen, and bee population), foraging activity, and honey production compared to the colonies fed only sugar syrup, and in most cases, colonies treated with Chlorella, Spirulina, and the mixture between all tested materials, it exhibited the best outcome in terms of all the tested parameters. Therefore, based on the results of our study, we conclude that chlorella, spirulina, and the mixture of all tested materials can enhance honeybee colony performance, which is reflected in foraging activity and final colony production of honey.

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