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Bee Pollinators Enhance B-onion Seed Production in the Dry Zone of Sri Lanka

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Production of B-onion (*Allium cepa*), a key cash crop in Sri Lanka, falls short of consumer demand due to limited quality seeds and high cost of commercial seeds. This study investigated the role of insect pollination on B-onion seed production in the dry zone, Sri Lanka, focusing on key pollinators, seed yield, weight and germinability. Experimental plots were established in a home garden in Sigiriya, selecting 50 umbels; 25 opened to insects and 25 covered. Diurnal insect visits and floral resources were observed. Seed yield and germinability were compared between opened and covered flowers. *Halictus lucidipennis* was the highest frequent visitor, followed by *Apis cerana* and *A. florea*. Nesting sites of *H. lucidipennis* were observed within the plots. Bee visitation was higher between 8:00–9:00 am, coinciding with pollen foraging, while nectar foraging remained throughout the day. The species-specific foraging patterns highlighted that *H. lucidipennis* and *A. cerana* were most active around 8:00–9:00 am for pollen foraging, whereas *A. florea* preferred midday (between 12:00–1:00 pm) for nectar foraging. *Apis cerana* preferred nectar foraging around 4:00–5:00 pm. Open umbels had significantly higher seed number and weight than covered umbels ($P = 0.00$). Germination percentage was also significantly higher in open-pollinated seeds than covered seeds using both petri dish and envelope methods ($P = 0.02$ and $P = 4.007\text{e-}06$), with longer seedlings after eight days ($P = 0.00$ and $P = 4.499\text{e-}11$). These findings highlight the importance of bees in enhancing B-onion seed production. Future research should assess next-generation plant vigor and compare pollinator efficiency.

Keywords: B-onion seed production, Germinability, *Halictus lucidipennis*, Insect pollination, Visiting pattern

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BACKGROUND

B-onion (*Allium cepa* L.) is a globally important vegetable valued for its versatility in culinary applications (Devi et al. 2014) and enrichment with nutrients and medicinal values such as anticarcinogenic, antiplatelet, antithrombotic and antibiotic properties (Leskovar et al. 2012). It ranks second in the global vegetable cultivation (Sansan et al., 2024), with an annual production cultivated exceeding 60 million tons (Gelaye et al. 2024). Originating from Central Asia, the onion is now widely grown in major onion-producing countries, including China, India, the Netherlands, Pakistan, Bangladesh and Australia (Sable et al. 2021). Onions require long days and ample sunlight to initiate growth and shorten the maturation period (Hahn et al. 2024). Rainfall influences onion farming as excessive rainfall during monsoons hinders growth, limiting cultivation to the summer period in such regions (Salunkhe et al. 2022). Optimal growth conditions include around 70 % relative humidity, at least 20% moisture for better seed germination (Patel et al. 2023), and fertile, well-drained soils (Zakirullah et al. 2018).

Quality onion seeds with proper weight, good appearance and high germinability are essential for successful onion production. As a biennial crop, onions produce bulbs in the first season, which are then replanted in the next season to generate seeds (Sidhu et al. 2004). However, onion seeds have a high moisture content and limited storage capacity, making them prone to reduced viability, germinability, and quality over time (Kamaei et al. 2024). According to Sidhu et al. (2004), to ensure optimal production, the use of freshly produced seeds for bulb cultivation is crucial.

Onion, particularly B-onion, depends heavily on cross-pollination (Paschapur et al. 2022). Its flowers form an inflorescence called an umbel and exhibit strong protandry, where the male part matures before the female part. Due to the presence of sticky pollen, insect-mediated pollination (entomophily) is essential for ensuring optimal seed set and high-quality seed production (Baswana 1984). Manual pollination is a popular artificial technique in agriculture, offering precise control over the pollination process and ensuring the hybrid nature of F1 seeds (Mardini et al. 2023). However, it is labour-intensive, time-consuming (Colombo and Galmarini 2017), and may damage pollen and stigma, potentially reducing operational efficiency.

Honeybees are the primary pollinators of onions. According to Chandel et al. (2004), bees contribute 60% - 95% of pollination in onion umbels, as observed in Himachal Pradesh, India and bee-pollinated umbels produce up to 10-11 times more seeds than covered control umbels. Further, *Apis dorsata* (Hymenoptera: Apidae) and *Apis cerana indica* (Hymenoptera: Apidae) were the most efficient pollinators (Devi et al. 2014). Additionally, Syrphid flies, bumblebees, halictid bees, butterflies, and various minor insects contribute to B-onion pollination (Bukhari et al. 2024; Sajjad et al. 2008). Therefore, insect pollination, particularly by bees, is crucial for successful B-onion seed production.

B-onion is an economically significant cash crop in Sri Lanka (Gunaratna et al. 2023) and is classified as an introduced species to the country during the 1960s (Pathirana et al. 2014). As mentioned in Pathirana et al. (2014), the first recorded seed production and evaluation trials have been conducted in 1964, and the period between 1960-1990 showed major advancement in onion cultivation, contributing to its agricultural importance.

As per the latest findings from the Department of Census and Statistics in Sri Lanka (2025), the cultivation of B-onions in Sri Lanka is mainly concentrated in Anuradhapura, Polonnaruwa and Matale districts, including Mahaweli areas, which provide optimal conditions for onion farming. B-onion is a seasonal crop, primarily grown during the Yala season. Despite a consistent annual consumer demand of approximately 289,757 metric tons (MT), the national production is significantly low, reaching only about 68,704 MT in 2021 (Department of Census and Statistics, Sri Lanka 2021). Due to this concern, the government incurs high costs for importing onions, with a Special Commodity Levy of Sri Lankan Rupees (Rs.) 15.00 per kilogram in 2020, as outlined in the Special Commodity Levy Act, No 48 of 2007 (Sri Lanka Customs 2021).

Local farmers' insight suggests the lack of quality seeds as a major challenge. According to personal communication, seed demand is further influenced by seed quality, availability, and affordability. Imported seeds are often expensive and fail to deliver expected results under local environmental conditions. Further, locally produced seeds can be sold at high prices, ranging from Rs. 30,000 to Rs. 35,000 per kilogram. Additionally, when using commercial seeds, about 3 kg per acre is required for maximum yield, while from their own farms, only 2.5 kg per acre is needed. These facts indicate that locally produced seeds may be of higher quality than commercial seeds. Vernalization, the process of exposing onion bulbs to low temperatures to promote uniform growth and flowering, is a significant step in seed production (D'Angelo and Goldman 2018). To achieve this, farmers often transport bulbs from Sigiriya to Rahangala, Nuwara Eliya (Samantha et al. 2013), which incurs additional costs. Concerns exist about how transportation may affect bulb quality and seed yield. The regional agriculture inspector of the Dambulla area suggests that training farmers to vernalise bulbs in their home refrigerators could reduce damage that might occur during transportation and potentially improve seed yield.

Onion seed production in Sri Lanka relies on both insect and manual pollination. According to personal communication with onion farmers in the Sigiriya area, onion seed production involves manual pollination methods, such as touching flowers with a palm or dragging cloth across the plot, which can damage flowers and waste pollen, reducing yield compared to insect pollination. However, no studies have been conducted in Sri Lanka to identify insect pollinators of B-onion or assess their contribution to seed viability. Indeed, this enhanced awareness of the pollination process can translate into improved onion bulb harvests when farmers use seeds produced through proper pollination practices. Therefore, the present study was designed to investigate the impact of insect pollination, particularly bee pollination, on B-onion seed production in Sri Lanka by identifying insect visitors to B-onion umbels, examining their visiting patterns and floral resource use, and evaluating the contribution of insect pollination to seed set and germinability. It was hypothesised that insect-visited open umbels would produce a higher number of seeds and that seeds produced through insect pollination would exhibit higher germinability compared to those produced in the absence of insects.

MATERIALS AND METHODS

Study site

The study was conducted in a home garden at Sigiriya (latitude 7°57'14.99"N, longitude 80°45'20.99"E) area that lies in the dry zone of Matale District, Central Province, Sri Lanka. The dry zone is characterised by its lowland plains and a few isolated hills, which cause it to experience distinct climatic conditions (Dissanayake et al. 2014). The tropical dry hot monsoon climate has affected this area, and it is characterised by a bimodal pattern of rainfall (Dilanjani et al. 2022). The mean annual daytime temperature hovers around 30°C, but temperature can occasionally rise to 37°C (Dissanayake et al. 2014). This climate features a long dry period before the main rainy season, known as “Maha”, from October to January during the north-east monsoon (Dilanjani et al. 2022). In addition, this region experiences desiccating winds during the long, hot south-west monsoon from May to August in the “Yala” season (Dilanjani et al. 2022). Thaufeek et al. (2014), in their study, highlighted the cultivation practices in the “Yala” and “Maha” seasons in the Sigiriya area. They reported that 81% of the upland plots are cultivated during the “Yala” season, while only 11% are cultivated during the “Maha” season. The main crop grown in these upland cultivation practices is B-onion. This indicates a significant preference for cultivating during the “Yala” season and a focus on onion as the main crop in these upland plots in the Sigiriya area.

Planting B-onions

Processing bulbs, plot preparation and growing B-onion were done under the supervision of the Dambulla Regional Agriculture Inspector and an experienced farmer who had experience with B-onion seed production. Accordingly, a suitable open land was selected in the home garden to prepare the B-onion plots. Six plots were prepared with measurements of five feet in length, two feet in width (Fig. 1). The soil is loam and somewhat sandy. The soil in each plot was loosened and mixed with 100 g of fertiliser, Triple Super Phosphate (TSP) and Urea (purchased from the Agriculture Department).

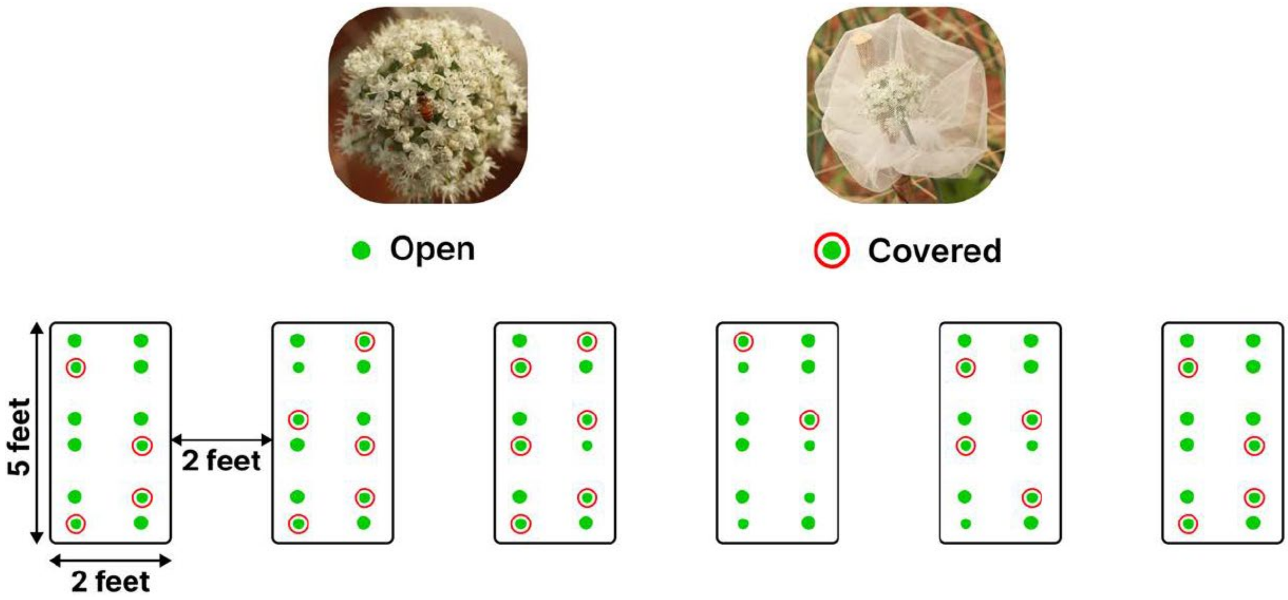

Fig. 1. Plot arrangement with covered and open umbels prepared for the study.

Quality mother bulbs (Local breed) that are suitable for seed production were purchased from a local farmer. Eighty medium-sized mother bulbs with healthy appearance, colour, and absence of diseases or damages were selected. They were vernalized by placing them in a refrigerator (10C) for 12 ˚days. Thereafter, the dried cell layers around the bulbs were removed. By this time, most of these onion bulbs contained new leaves and roots. The bulbs with leaves were trimmed a little. Thereafter, the bulbs were washed thoroughly with a commercial fungicide (OasisCaptan 50% (w/w) (20 g in 10 L of water)) liquid for about 10–15 minutes to prevent fungal infections.

Of the treated eighty, healthy 72 bulbs were planted in plots. Each plot contained 12 plants, arranged in two rows (six plants in one row). Plants were monitored daily to observe their growth progress, and watered daily from shoot to root using a sprinkler water bucket to maintain adequate moisture levels. Following recommendations, 100g of Urea and 200 g of Blue Corn fertiliser were added after 10 days, 200 g of Blue Corn fertiliser was added after 17 days, and 200 g of Murate of Potash was added after 23 days of planting to ensure optimal growth and development. Fungicides are important to avoid fungal infections. Oasis Captan 50% (w/w) (20 g in 10L of water for 60 ft^2) was added again after five days of planting. HOMAI (manufactured by Japan Holdings (Pvt) Ltd, Sri Lanka) is one of the fungicides used for fungal infections of B-onion bulbs (10 g in 10L of water for 60 ft^2). CG Mancozeb 80% (w/w) WP (manufactured by CIC CropGuard (Pvt) Ltd, Sri Lanka) was another fungicide used for fungal infections of leaves (20 g in 10 L of water for 60 ft^2). These two fungicides were used once every five days alternatively, and this continued until the seeds were harvested. B-onion umbels appeared after 24 days. When the umbel became large, before flowering, a gill net was arranged through the farm area below the umbels to give support to the long stalk to bear the weight of the umbel. The water supply system was changed from pouring to flowing through canals to the plots to prevent washing out flower pollen.

Identifying insects visiting B-onion umbels and studying their visiting patterns and floral resources

B-onion bushes were numbered from 1-72. One umbel from each plot was randomly selected and a total of six umbels were selected for a one-hour observation period. Each umbel was observed for five minutes for visiting insect species, and numbers were recorded. During the observation period, photographs of insects that visit umbels were taken. Species identification was carried out using high quality photographic records, insect identification guides by Devi et al. (2017), Zinzuvadiya et al. (2020) and the bee identification key (Karunaratne and Edirisinghe 2008) and were cross-checked with the expert identified specimens lodged in the ISDF (Invertebrate Systematics and Diversity Facility) collection, Department of Zoology, University of Peradeniya. Furthermore, observations were made on whether the bees take nectar or pollen (evident by their activity in flowers). All six umbels were observed in the same manner during a one-hour duration. Another set of umbels from each plot was selected for the next round. These observations were taken from 6:00 am to 5:00 pm on two days in the early stage of flowering, five days in the peak stage of flowering and two days in the latter flowering stage. Flowering stages were defined qualitatively rather than based on quantitative thresholds.

Assessing the contribution of insect pollination to B-onion seed production

A set of 25 umbels to include a few (2–6) from each plot was randomly selected, labelled, and individually covered using a fine mesh (diameter: 1mm, > 40-mesh screen) net to deter insect visits (Taki, 2020) at the onset of flowering. As stated by EyouAgro (2023), a 40-mesh screen permits sufficient airflow and maintains temperature close to ambient conditions. Therefore, any temperature increase within the covers is expected to be minimal. Another set of the same number of umbels selected from each plot were labeled “kept open” for visiting insects. On maturity, these labelled umbels were harvested separately when 10% of black seeds were visibly exposed in the umbel and were separately air dried (Adel 2013), seeds were removed and counted. In the Entomology Laboratory, Faculty of Science, University of Peradeniya, the seeds were weighed using AS 220.R2 PLUS Analytical Balance and were stored in the refrigerator (4°C).

Investigating the germinability of seeds produced through insect pollination vs. self-pollination

For the seed germination test, a completely randomised design was employed with three replications per seeds harvested from covered and opened umbels, each consisting of 50 seeds (Jagosz 2015). Following the Petri dish method described by Jeromini et al. (2019), seeds were evenly distributed on two layers of wet filter paper placed in 150 mm Petri dishes and were covered with a lid. Moisture was provided by daily spraying demineralised distilled water (Jagosz 2015). These covered Petri dishes were then placed inside loosely closed plastic bags to maintain the moisture level. After eight days, the average seedling length was measured by a ruler (Devi et al. 2015).

Another set of seeds was tested for germinability using the envelope method (Jeromini et al. 2019). Two rows of 25 seeds were sown on the upper half of a horizontally laid moistened paper towel. To prepare the envelope, the sheet was folded in half, encasing the seeds between two halves of the paper towel. Next, ¼ of the left side and right side were folded inward and the envelope was then completed by folding it vertically at the meeting point of the edges, with the opening positioned upwards. Three replicates from both covered and opened seeds were prepared with 50 seeds each. The envelopes were daily sprayed with water and were placed inside transparent plastic boxes with loosely closed lids and arranged at about a 45 ° angle to the horizontal. After eight days, seedling length of each seed was measured using a ruler.

Data analysis

Visiting patterns of insects were plotted using Sigmaplot 15.0 and MS EXCEL. Differences in insect visitation and foraging behaviours were assessed using the Kruskal-Wallis test, followed by post hoc pairwise comparisons where appropriate. A two-sample t-test was used to assess the seed set, while the Mann-Whitney U test and Two-sample t-test were used to assess the germinability of seeds between covered and open umbels. All tests were conducted at a significance level of $P < 0.05$ using R Software, Version 4.3.2.

RESULTS

Growth of B-onion plants

The complete growth cycle of B-onion spanned approximately three and a half months. After the initial preparation and planting of mother bulbs on 26th May, 2024, germination was visible by 8th June, 2024. As the seedlings developed, significant growth and establishment were evident by 13th June, and flower buds appeared by 25th June. The Buds started to flower around 10th July, with peak flowering by 27th July. The whole flowering period lasts for about one month. After the flowering period, the flower structures started maturing around late August, and by the end of the growth cycle, the dried flowers were harvested during the last weeks of September 2024.

Insect visiting B-onion umbels, their visiting patterns and floral resources

Eight species of insects belonging to four orders (Hymenoptera, Diptera, Lepidoptera and Hemiptera) visited onion umbels during the flowering period. Hymenopterans were the most dominant flower visitors represented by three species: *Halictus lucidipennis* Smith, 1853 (Hymenoptera: Halictidae), *Apis cerana* Fabricius, 1793 (Hymenoptera: Apidae), and *Apis florea* Fabricus, 1787 (Hymenoptera: Apidae).

Among them, *H. lucidipennis* was the most abundant species with 1,104 visits, followed by the two honey bee species, *A. cerana* with 1056 visits and *A. florea* with 432 visits. Other insect species were very rare visitors; a bug *Dysdercus cingulatus* Fabricius, 1775 (Hemiptera: Pyrrhocoridae) with four visits, a moth (Lepidoptera: Scythrididae) with three visits, a hoverfly (Diptera: Syrphidae) with two visits, and the two other dipteran species (Family Stratiomyidae and Family Tachinidae) each with only a single visit. During the flowering stage of B-onion, a few female individuals of the ground-nesting sweat bee, *H. lucidipennis* were observed making nests under plants and shaded areas along the edges of the onion plots without a ground cover.

Visiting patterns of the most commonly observed three species of bees showed temporal fluctuations across different hours and intensity of flowering. Descriptively, *A. cerana* exhibited a higher visitation frequency during the early flowering stage, particularly in the early morning and late evening hours. However, during the peak flowering stage, *H. lucidipennis* showed comparatively higher visitation frequencies, which gradually decreased toward the end of the flowering stage, especially in the early mornings. Despite this shift, *A. cerana* maintained a relatively consistent visiting pattern throughout the entire flowering stage. *Apis florea* displayed a gradual increase in visiting frequency from the early flowering stage to the peak flowering stage, followed by a steady decline in visits towards the end of the flowering stage. They were most abundant at noon.

According to the overall diurnal visitation pattern of bees as illustrated by figure 2, daily visits of bees to B-onion umbels commenced shortly after sunrise, generally between 7:00 am and 8:00 am. Visitation frequency increased sharply in the morning, reaching an apparent maximum around 8:00-10:00am with an average of approximately 50 visits per umbel. Thereafter, a gradual decline in the overall visitation rate was observed toward the afternoon and evening (up to 5:00 pm), with a slight increase in frequency between 3:00 pm and 4:00 pm. Although overall visitation differed significantly across whole flowering period (Kruskal-Wallis test, $P < 0.05$), pairwise comparisons among hourly intervals were not statistically significant, suggesting that observed fluctuations are most probably due to temporal trends.

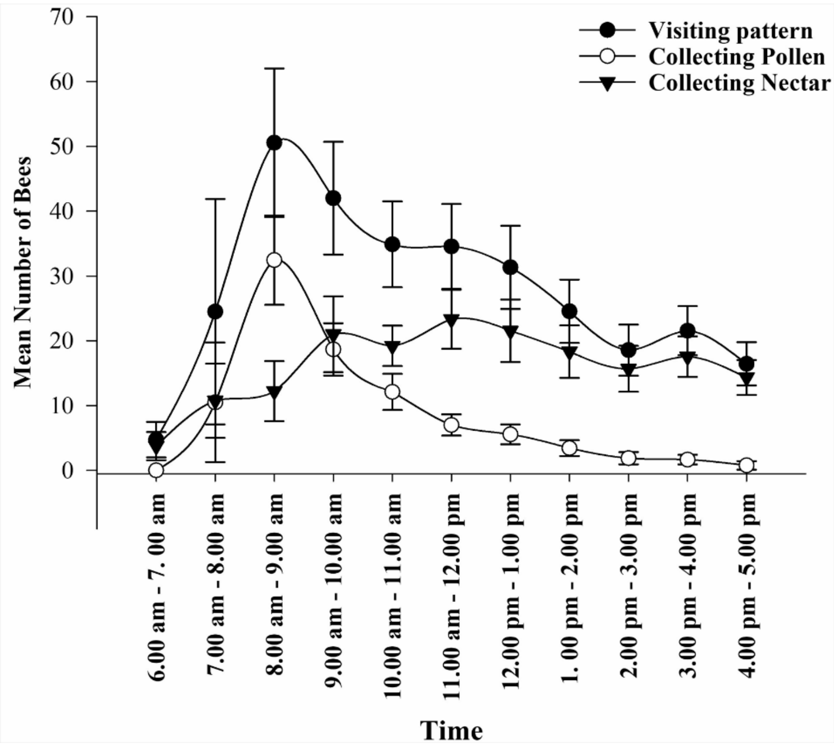

Fig. 2. Overall diurnal visiting pattern and pollen and nectar collecting pattern of bees visiting B-onion umbels per hour during the flowering period from 26.07.2024 to 25.08.2024 (9 days). Values

represent mean ± SE numbers of bees observed at different time intervals. Visitation across the flowering period showed a significant overall effect (Kruskal-Wallis test, $P < 0.05$); however, pairwise comparisons among hourly intervals were not significant. Pollen foraging also differed significantly over time, but no pairwise differences were detected. In contrast, nectar foraging showed no significant variation across time intervals.

Further, the overall diurnal foraging pattern of bees, whether collecting pollen or nectar during their visits to B-onion umbels, is depicted in figure 2. Accordingly, the overall pollen-collecting pattern resembles the overall bee-visiting pattern with higher activity observed during the morning hours, between 8:00 am and 10:00 am, followed by a gradual decline towards 5:00 pm. In contrast, nectar gathering showed relatively higher activity between 9:00 am and 10:00 am, and remained comparatively steadily throughout the day, with apparent increases around 9:00 am to 10:00 am, 11:00 am to 12:00 pm, and again between 3:00 pm and 4:00 pm. Notably, some bees collected both pollen and nectar during the same foraging trip. Statistical analysis using the Kruskal-Wallis test indicated a significant difference in pollen foraging activity across time intervals in the overall model ($P = 4.482e\text{-}05$); however pairwise comparisons did not reveal significant differences between time intervals. In contrast, nectar foraging activity did not differ significantly across time intervals in the overall model.

According to figure 3, which depicts the diurnal visiting pattern and foraging activities of each bee species, the number of visits of *H. lucidipennis* (Fig. 3A) showed a rapid increase in the early morning with the highest observed activity between 8:00 am. and 9:00 am. A similar pattern was observed for pollen collection, but with a very low number after 11:00 am, while the nectar gathering pattern remained relatively steady from 9:00 am to 2:00 pm and declined thereafter. The number of visits of *A. cerana* (Fig. 3B) showed a rapid increase in the early morning, with the highest observed visitation between 8:00 a.m. and 9:00 a.m. Nectar gathering showed a marked increase during this period, surpassing pollen collection. As the day progressed, the intensity of visiting patterns decreased and stabilized after 11:00 am. However, slight increases in both nectar gathering and visitation were observed in the late afternoon, between 3:00 pm. and 5:00 pm. *Apis florea* (Fig. 3C) showed relatively higher early morning activity between 8:00 am. and 9:00 am., during which nectar gathering slightly surpassed pollen collection. Additional increases in nectar foraging were observed between 12:00 pm.–1:00 pm. and 3:00 pm.–4:00 pm. Pollen collection increased rapidly in the morning with the highest activity between 8:00 am. to 9:00 am. and declined thereafter. Kruskal-Wallis test revealed a significant difference in visitation frequency across time intervals only for *H. lucidipennis* when considered as a single model ($P = 0.0020$); however, subsequent pairwise comparisons did not reveal significant differences between specific time intervals. For *A. cerana* and *A. florea*, no significant differences in visitation frequency or foraging behaviour were detected between different time intervals ($P > 0.05$).

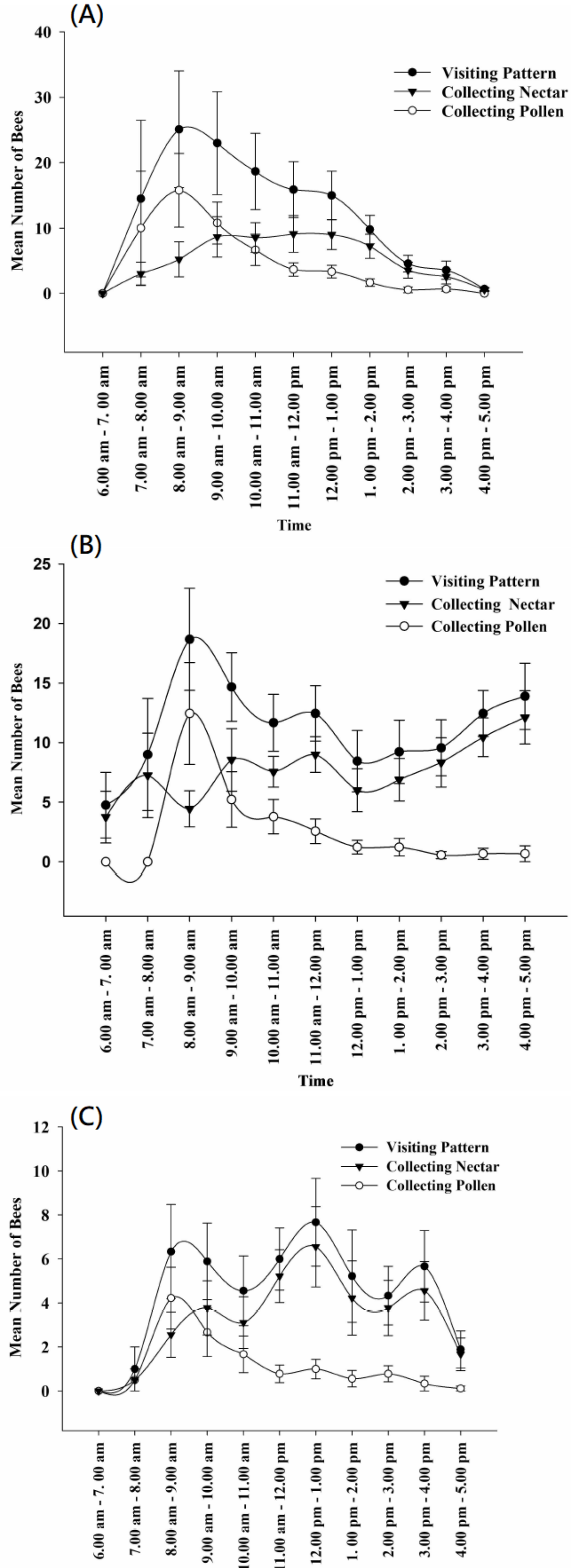

Fig. 3. Diurnal visiting pattern and foraging pattern of bees during the flowering period of B-onion in the dry zone, Sri Lanka. (A) *Halictus lucidipennis* (B) *Apis cerana* (C) *Apis florea*. Values represent mean ± SE numbers of bees observed at different time intervals. Kruskal-Wallis test showed a significant difference in visitation frequency over time only for *H. lucidipennis* (*P* =

0.0020), but post hoc pairwise comparisons were not significant. In contrast, *A. cerana* and *A. florea* showed no significant differences in visitation or foraging behaviour across time intervals.

Contribution of insect pollination to B-onion seed production

As shown in figure 4A, the mean number of seeds per opened umbel was 537 ± 33, while that of covered was 134.2 ± 15. According to the two-sample *t*-test, the number of seeds per umbel resulted from the covered and opened umbels had a significant difference (P = 5.459e-15). Similarly, mean weight of seeds per covered and opened umbel (Fig. 4B) were 0.5337 ± 0.064 g and 2.105 ± 0.13 g, respectively and was a significant difference (P = 8.258e-15).

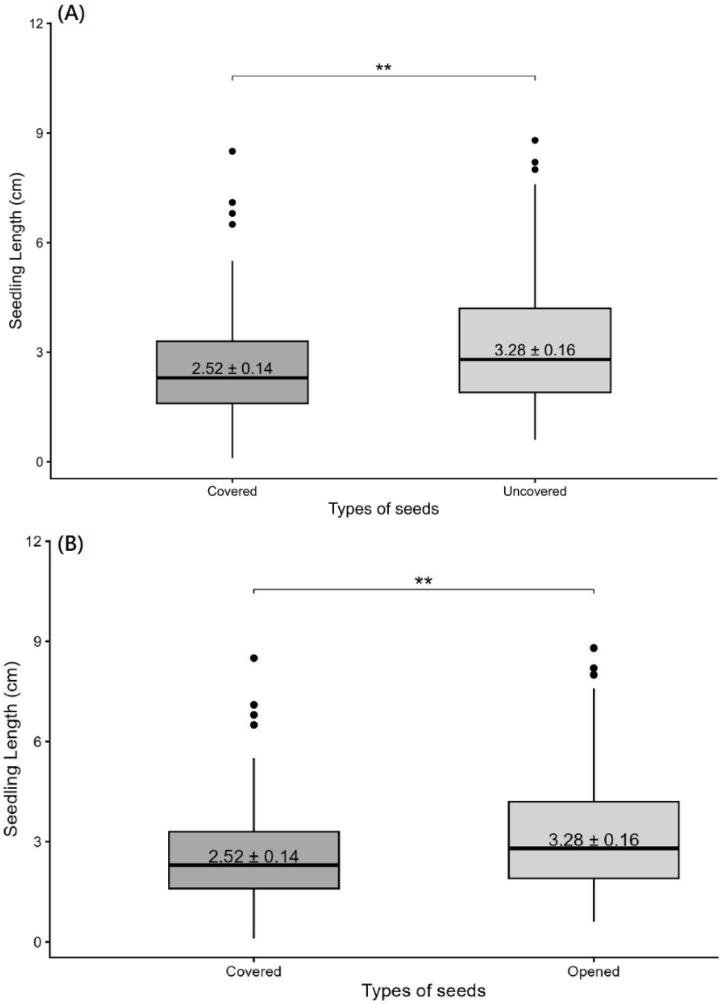

Fig. 4. Contribution of the insect pollination in B-onion seed production (A) Average number of seeds produced per umbel (B) Average weight of seeds produced per umbel resulted from covered and opened umbels. Values represent mean ± SE. The number of seeds per open umbel (537 ± 33) was significantly higher than that of covered umbels (134.2 ± 15) (two-sample t-test, P = 5.459e-15). Similarly, the mean seed weight per open umbel (2.105 ± 0.13 g) was significantly higher than that of covered umbels (0.5337 ± 0.064 g) (two-sample *t*-test, P = 8.258e-15). Asterisks indicate significant differences (*P < 0.05; **P < 0.01, ***P < 0.001).

Germinability of B-onion seeds from covered and open umbels

Germination test in Petri dishes

Seeds of both groups developed into seedlings after eight days of germination in Petri dishes. Seeds of opened umbels showed an 89.33% germination, while it was 79.33% for the seeds of covered umbels figure 5A). According to the two-sample t-test, the germination percentages of the two treatments had a significant difference (*P* = 0.026). As the Shapiro-Wilk test indicated that seedling length of both covered and opened seeds was not normally distributed, the Mann-Whitney U test was carried out to analyse the seedling length. Accordingly, the mean value of seedling length of seeds of opened umbels was 3.28 ± 0.16 cm, while that of seeds of covered umbels was 2.52 ± 0.15 cm (Fig. 5B), showing a significant difference (*P* = 0.001).

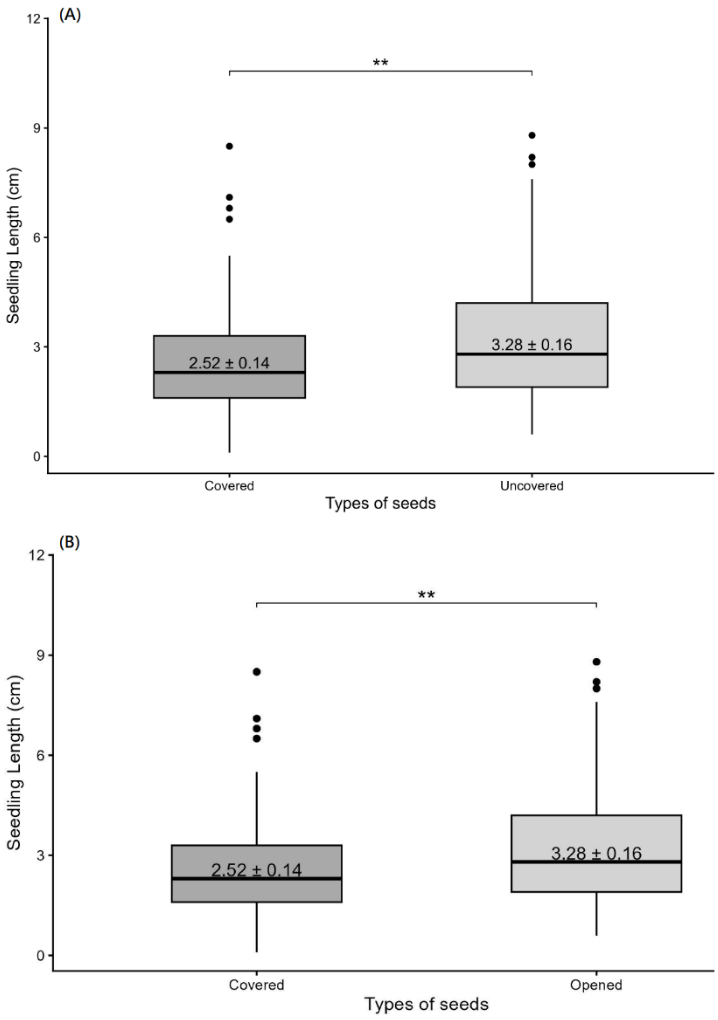

Fig. 5. Seed germination in Petri dish method. (A) Germination percentage and (B) Seedling length of seeds resulted from covered and open umbels. Values represent mean ± SE. Germination percentage was significantly higher in open umbels (89.33%) than in covered umbels (79.33%) (two-sample t-test, *P* = 0.026). Seedling length was also significantly higher in open umbels (3.28 ± 0.16 cm) compared to covered umbels (2.52 ± 0.15 cm) (Mann-Whitney *U* test, *P* = 0.001). Asterisks indicate significant differences (**P* < 0.05; ***P* < 0.01, ****P* < 0.001).

Germination test in Envelope method

B-onion seedlings emerged after eight days of germination in envelopes. Seeds of open umbels showed a 93.33% germination while that of covered umbels was 72.67% (Fig. 6A), indicating a significant difference (two-sample t-test, P = 4.007e-06). Mean value of seedling length of seeds of open umbels was 4.46 ± 0.14 cm, while that of covered umbels was 3.20 ± 0.11 cm (Fig. 6B) indicating a significant difference (Mann-Whitney U test, P = 4.499e-11).

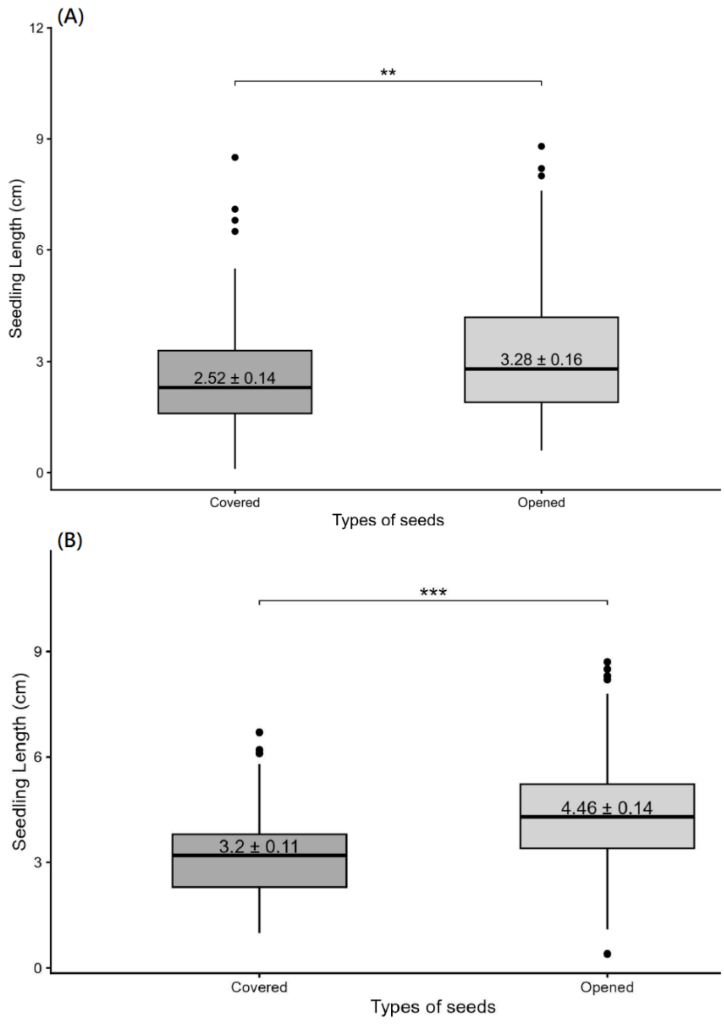

Fig. 6. Seed germination in Envelope method. (A) Germination percentage and (B) Seedling length of seeds resulted from covered and open umbels. Values represent mean ± SE. Germination percentage was significantly higher in open umbels (93.33%) than in covered umbels (72.67%) (two-sample t-test, P = 4.007e-06). Seedling length was also significantly higher in open umbels (4.46 ± 0.14 cm) compared to covered umbels (3.20 ± 0.11 cm) (Mann-Whitney U test, P = 4.499e-11). Asterisks indicate significant differences (*P < 0.05; **P < 0.01, ***P < 0.001).

DISCUSSION

Pollination of B-onion flowers is facilitated by a broad array of insects such as bees, flies, moths, and bugs, with variations in community composition across different ecological and climatic zones. The present study investigated the crucial role played by insect pollinators in B-onion seed production in the dry zone of Sri Lanka during the Yala season, spanning from late April to September 2024. The most frequent visitor was a sweat bee, *H. lucidipennis* followed by two species of honeybees, *A. cerana* and *A. florea.* However, this observation partially contrasts with findings of Devi et al. (2014), who demonstrated that Asiatic giant honey bee (*A. dorsata*), western honey bee or the European honeybee (*A. mellifera*), common honey bee (*A. cerana*) and, dwarf honey bee (*A. florea*) as the dominant pollinators of B-onion flowers in CCS Haryana Agricultural University, Hisar, India. Also, Mazeed and Marey (2018) have mentioned that honey bees as most predominant pollinators of onion; the findings of the current study indicate that solitary bees surpass them in abundance. Although *A. mellifera* is absent in Sri Lanka, *A. cerana* and *A. florea* were observed visiting onion flowers in this study but numbers were less than *H. lucidipennis*. The absence of *A. dorsata* in this study could be attributed to their nesting preferences, as they predominantly nest in tall trees and rock caves, which were often scarce in the present agricultural landscape, limiting their presence in onion flowers (Saberioon et al. 2010). However, predominance of honey bees ranging from 60% to 95% was recorded by multiple studies in both tropical and temperate zones, which are Jadhav (1981), Parker and Hatley (1979) and Singh and Dharamwal (1970). This difference in species dominance may be attributed to local habitat suitability for pollinators. According to Attigeri et al. (2024), as fields were located closer to urban areas, large water tanks, coconut plantations, banyan trees and tall buildings could have provided favourable nesting and foraging habitats for honey bees. In contrast, the fields in the present study were mostly open landscapes and situated far away from open water sources, as farmers primarily supplied water through pipelines, which may have reduced habitat suitability for honey bees.

Apart from bees, B-onion umbels were rarely visited by a few individuals of hemipteran bugs, a lepidopteran moth, and three dipteran species. Although some previous studies show a high preference of dipterans for onion flowers (Mazeed and Marey 2018), and even the highest preference in certain cases (Hwang et al. 1998), the present study did not show such a trend. Also, the present study recorded a relatively low number of insect species visiting B-onion umbels compared to other similar studies. According to Divija et al. (2022), the pollinator community visiting B-onion flowers at ICAR- Indian Institute of Horticultural Research in Bengaluru, India, from 2019 to 2021, compromised 59 species across five insect orders. Similarly, Sajjad et al. (2008) mentioned that onion umbels attract a wide variety of insect visitors in Pakistan. This trend can be due to the composition and abundance of insect fauna which are influenced by factors such as geographical location, latitude, and temporal variations (Ollerton and Cranmer 2002; Venkatesh et al. 2019). However, Walker et al. (2011) demonstrated that although small arthropods such as flies and thrips were present in onion seed fields, their role in pollination was minimal.

It is noteworthy to observe a few ground nests of *H. lucidipennis* in the onion plots. Tsiolis et al. (2022) highlighted that ground-nesting bees tend to prefer soils with specific attributes, such as moderate stoniness and optimal moisture levels, which are aligned with the soil conditions of the current study. During the study period, the foraging population of bees was highest in the mid-flowering period, while their activity was relatively low at the beginning as well as the end of the flowering period. This pattern has also been documented in previous studies by Attigeri et al. (2024) and Devi et al. (2014). The number of opened flowers was higher during the mid-flowering period compared to the early and late phases, provided greater floral rewards and thereby attracted more bees. The overall diurnal visiting pattern of bees to B-onion umbels with a major peak between 8:00 am –9:00 am can be attributed to several factors such as temperature, light intensity, humidity (Kamaraj and Rasappan 2024), their circadian rhythm (Frisch and Aschoff 1987), reward availability, floral display and competition with other foragers (Stabentheiner and Kovac 2016). According to Silva and Dean (2000), the concentration and production of nectar are crucial factors in attracting bees, as they are attracted to flowers with abundant nectar. This nectar is often more readily available during mid to late morning and late evening, aligning with the peak foraging time of different types of bees (Silva et al. 2004).

The current study highlighted three visiting frequency patterns for the three bee species attracted to B-onion flowers. Accordingly, the visiting frequency of *H. lucidipennis* was higher in the mornings, while in the evenings it was notably lower than in the mornings. Nye et al. (1971) stated that this type of visiting pattern can be attributed to pollen viability, which is 2-3 times higher in the morning than in the afternoon. In the evenings, their foraging shifted to collecting nectar. Korichi et al. (2021) state that halictid bees are important pollinators, engaging in mixed pollen and nectar collection. The common honeybee, *A. cerana* was observed consistently throughout the flowering period with two peak times during early mornings (8:00 am–9:00 am) and late evenings (3:00 pm –4:00 pm) in a day. The study conducted by Kamaraj and Rasappan (2024) revealed that their visits were significantly higher under conditions of low temperatures, minimal solar radiation, reduced precipitation and elevated relative humidity. Further, this study demonstrated that, notably, *A. cerana* completed the majority of their flower visits (90%) during the early morning hours, and they preferred collecting pollen during the morning and nectar during the evening. *Apis florea* plays a vital role as a pollinator of onion flowers accounting for more than 94% of the total flower visitors in some studies (Abrol 2010). Considering the current study, *A. florea* was mostly observed during the noon (12:00 pm–1:00 pm) with high sunlight and temperatures. These conditions are optimal for engaging in massed flight activity of *A. florea* (Bhagavan et al. 2016). Further, they mainly focused on collecting nectar in the noon rather than collecting pollen. Similarly, previous studies have shown that their foraging activity peaks during mid-day when temperatures are high and relative humidity is low (Kachhawa 2022). Therefore, they reduced competition with other bees for forage in onion flowers through this distinct visiting pattern in the noon for collecting nectar (El Shafie et al. 2002). Accordingly, in the current study, *H. lucidipennis* primarily collected pollen while *A. florea* was collecting nectar. However, *A. cerana* preferred both nectar and pollen similarly. Most studies on B-onion seed production state that honeybees are the main pollinators of B-onions (Benedek 2009) and carry more pollen on their bodies than other insects (Free and Williams 1972). However, according to Parker and Hatley (1979), this pollen is less viable for onion pollination. Therefore, solitary bees are often better at pollinating onion flowers than honeybees, likely because they transfer healthier pollen or are better suited to pollination (Brand 2014). During the current study, the most common sweat bee, *H. lucidipennis* could be advantageous to the successful pollination of B-onion umbels in the study area. Furthermore, Monasterio et al. (2023) highlighted that onion pollen is rich in protein, a critical nutrient for bee brood growth, making it an essential and attractive resource for pollen collecting species.

Onion is a crop requiring cross-pollination for optimal seed production. Self-pollination studies done by covering umbels resulted in significantly lower yields and seed quality (Wilkaniec et al. 2004). The current study revealed that open umbels visited by bees produced a significantly higher number of seeds and weight per umbel compared to those from covered umbels not visited by bees. Further, the covered umbels contained numerous incomplete seeds, while those from open umbels were well developed, indicating a higher pollination efficiency in open umbels visited by bees. Also, both the petri dish method and envelop method highlighted that the seeds from open-pollinated umbels had higher germinability compared to those from covered umbels. Moreover, the length of the seedlings of open umbels was significantly higher than covered seeds. A similar experiment done in Egypt for seed count, Mazeed and Marey (2018) stated that covered (caged) plants produced significantly fewer seeds (45.40–47.60 seeds/20 umbels) compared to open-pollinated plants, which yielded 711.60-721.10 seeds/20 umbels. Further, according to Devi et al. (2015), in Hisar, India, the impact of various pollination methods on the yield of B-onion seeds revealed that the highest number of seeds per umbel was achieved with a combination of open-pollinated and hand-pollinated umbels (1430 seeds per umbel). This was followed by open pollination alone (1247 seeds per umbel), bee pollination (using only *Apis mellifera* in a cage) (1217 seeds per umbel), and hand pollination (956.6 seeds per umbel). In contrast, the lowest seed set was recorded in umbels where pollinators were excluded using cages, allowing only self-pollination, resulting in just 90 seeds per umbel. A similar trend was observed in the difference in seed numbers between open-pollinated and covered umbels in the present study. However, Devi et al. (2015) highlighted the effectiveness of combining hand pollination with open pollination, though it emphasized the requirement of advanced technical skills for hand pollination. Moreover, the study highlights that there is no considerable difference between open -pollination and bee-pollination alone. Furthermore, according to Divija et al. (2022), a study conducted in ICAR-Indian Institute of Horticultural Research, Hesaraghatta, Bengaluru Karnataka, India revealed that bee-pollinated umbels produced the highest number of seeds (777.60 ± 57.60) than other techniques: open pollination (749.20 ± 47.57 seeds per umbel), hand pollination (459.40 ± 35.97 seeds per umbel) and covered umbels (self-pollination) (34.40 ± 9.91 seeds per umbel). Further, Chandel et al. (2004) recorded that bee pollination enhanced seed yield by 2.5 times, with an average of 971 seeds per umbel compared to 406 seeds in the control group. According to Parker (1982), in the USA, *Halictus ligatus* was shown to be more efficient pollinator of B-onion than honeybees, resulting in higher seed set and lower seed abortion rate. In contrast, the present study focused on *H. lucidipennis*, and differences in behaviour or efficiency among *Halictus* species are likely. Further, the present study only considered visitation frequency rather than pollination efficiency on the species. Therefore, direct comparison should be interpreted with caution. However, Silva et al. (2004) in the USA highlighted that successful pollination of onion flowers greatly depends on sufficient nectar production and honey bees are more attracted to them. When considering seed weight per umbel, similar result was given by several studies. According to Divija et al. (2022), seed weight per umbel in bee pollinated umbels was 3.33 ± 0.45, followed by open-pollinated umbels opened for all types of insects (3.10 ± 0.08), hand-pollinated (1.61 ± 0.14), and covered umbels (0.19 ± 0.06). Furthermore, Korichi et al. (2021) highlighted that a higher average weight of seeds was observed per open umbels (4.41 g) than that of covered umbels (0.09 g). It can be attributed to a greater number of seeds produced as a result of effective pollination. Moreover, the length of seedlings of open umbels was significantly higher than covered seeds. These findings align with a study conducted by Kumar et al. (1985) in Himachal Pradesh, India, which demonstrated a significant difference in seed germination between open-pollinated and covered (nylon cages of cloth bags) umbels. Therefore, it reveals the positive influence of open pollination on seed germinability.

CONCLUSIONS

The current study emphasizes several key findings regarding insect pollination on B-onion seed production in the dry zone environment of Sri Lanka. Bees were identified as the primary pollinators with *H. lucidipennis*, a solitary bee species demonstrating higher visitation frequency compared to the two honey bee species, *A. cerana* and *A. florea*. Most bee activity occurred during the early to mid-flowering stages, with peak foraging times in the mornings, 8.00 am–9.00 am. Notably, *H. lucidipennis* and *A. cerana* were most active in the mornings, while *A. florea* preferred afternoons with higher temperatures and greater light intensity. Cross pollination of B-onion umbels was found to be critical for seed production and seed germinability. Among potential pollinators, *H. lucidipennis* stands out as a suitable choice due to their high abundance and nesting within onion plots. For future research, the seeds resulted from the current study can be used to investigate the vigour of the next generation of plants and their reproductive success. Additionally, to identify the most efficient pollinators, experiments can be designed to investigate the amount of pollen deposition on anthers by each bee species and their contribution to seed set and their germinability.

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