The pollination biology of onion (*Allium cepa* L.)- A Review

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**ABSTRACT**

Managed pollination is an essential input in enhancing the crop productivity. In recent years, there has been an increase in the accumulation of data to indicate that seed yields of insect pollinated crops may often be lower than the expected, not because of adverse climatic, edaphic or cultural factors, but simply because the number of certain pollinators is inadequate. In absence of pollination in many entomophilous crops, fruit or seed set is affected adversely even if all the cultural practices are followed meticulously. Insect pollinators set a greater proportion of early flowers of the crop and increase quality and quantity of the seed yield. Before the use of managed pollination, it is necessary to have a basic knowledge of factors which influence pollinator activity and preference of the pollinators for different crops. This review summarizes the pollination biology of the important vegetable crop, *Allium cepa* L., commonly known as onion.

**Key words:** Abundance, Floral biology, Male sterility, Mode of pollination, Onion, Pollinators, Yield.

*Allium* is the genus of onions with about 1250 species of perennial bulbous plants. Onions are among the world’s oldest cultivated plants. They were probably known in India, China, and the Middle East before recorded history. Ancient Egyptians regarded the spherical bulb as a symbol of the universe. It is considered as native to southwestern Asia but is now grown throughout the world, chiefly in the temperate regions. Onion makes an important source of vegetable and its seeds are source of condiments (Baswana, 1984). There are several species of *Allium* or onion that are grown exclusively for their flowers instead of their bulbous structures. *Allium cepa* L. is a liliaceous crop, which is grown in different parts of world and its cultivation is becoming popular in a state like Haryana too (Sihag, 1985). In India it has been grown in 0.52 million ha with the production of 6.5 million tones (FAO, 2002). The productivity of onion in India is 12.5 t/ha, which is much lower than the productivity of USA (41.12 t/ha)(FAO, 2002). The higher productivity of onion in USA is due to the growing of the long day hybrids and crop varieties. The literature pertaining to floral biology, pollinators and their abundance, foraging behaviour, pollination efficiency and effect of mode of pollination on onion yield is reviewed below:

**Floral biology:** The crop is strongly protandrous; self pollination is largely absent which depends upon insects for cross pollination (Baswana, 1984). Inflorescence is present at the top of the green plant which is hollow from the inside. The height may vary from 0.9 m to 1.2m depending on the genotype and other factors. Flowers in the umbel are enclosed in a membranous 2-3 white coloured sheath called spathe. The sheath splits because of the pressure created by growing flowers inside the umbel. There may be 50 -2000 florets in an Inflorescence depending on the genotype, planting time, size and storage conditions of the mother bulb. The flowers are white to bluish in colour. The perianth segments are six in two whorls spreading, reflexed, free and ovate. The stamens are also six in two whorls. Anthers are bilocular and the ovary is superior. Anthers may be green or purple in colour depending upon genotype. The colour also changes with the age of flower. Some florets have two ovaries with seven stamens. Anthesis occurs in early morning (6-7 h). Anther dehiscence takes place between 7.00 and 17.00 h and on next day also with peak between 9.30 and 17.00 h. Pollen fertility is highest on the days of anthesis. Stigma receptivity is also high on the day of anthesis (Jones, 1933). The duration of anthesis is approximately four weeks on individual umbel. The anthesis begins from outer flowers and goes centrally in succession. The flower is protandrous in nature and stigma becomes receptive when shedding of pollen is over. Male-sterile and male-fertile lines differed in their stigma and style characteristics and pattern of development. At flower opening, the styles of male-sterile lines were longer and the stigmatic knob became receptive relatively sooner (Ali et al., 1984).
Diversity of insect visitors on onion umbels: Onion umbels are visited by honey bees, small syrphid flies, bumble bees, halictid bees, drone flies, butterflies and insects of minor importance with respect to pollination (Sajjad et al., 2008). The blossoms of onion are highly attractive to both pollen and nectar collecting insects (Free, 1993; Kordakova, 1956) and Sakharov (1956) gave major credit to the honey bee as a pollinator of onions in Russia. Bohart et al. (1970) reported 267 species of insect visitors on onion flowers, the most important of which were honey bees, small syrphid flies, halictid bees and drone flies. Of these, only the honey bee can be manipulated and used in large-scale onion seed production. Apart from honey bees, Halictus farinosus (Parker, 1982), butterflies (Jaboński et al., 1982; Bombyx occidentalis, Megachile rotundata, Osmia lignaria, Osmia cornifrons and Nomia melanderi) (Mayer and Lunden, 2001), Osmia rufa (Wilkaniec et al., 2002) and syrphid flies were also recorded to take part in the process of pollination (Chaudhary, 2004).

The predominance of honey bees in the range of 60-95 per cent was recorded by many workers (Singh and Dharamwal, 1970; Parker and Hatley, 1978; Jadhav, 1981; Kumar et al., 1985). Under sub-tropical conditions of Himachal Pradesh situated at an altitude of 1200 m above mean sea level, Apis dorsata, A. florea and syrphids (Episyrphus balteatus, Metasyrphus confrater and M. corollae) were important visitors (Chandel et al., 2004). Saeed et al. (2008) reported the presence of four bee species and twelve true fly species as community of pollinators on onion, whereas Shafqat and Masood (2008) reported two hymenopteran bees and eight true flies of Diptera as pollinators of onion crop.

Pollinator abundance and activity on onion umbels: For different crops, different pollinators are responsible to effect cross pollination. Almost every order of insects has been reported to play a role in the pollination of flowering vegetables and spice crops. McGregor (1976) and Free (1993) reported that insects like ants, aphids, bees, beetles, butterflies, flies, midges, mosquitoes, moths, thrips and wasps act as pollinators in cultivated crops. Among them, bees are considered to be the most important pollinators because they are the only insects whose immature stages are reared exclusively on pollen and nectar (Crane, 1990). Crailsheim (1991) has reported that the adult worker honey bees feed upon pollen to produce royal jelly for the queen bees, the brood, the adult workers of different age and the drones. The younger bees are the nurse bees which feed upon pollen mainly to produce royal jelly from their highly developed hypopharyngeal glands. Priti and Sihag (1997) found that pollen, nectar sugar concentration, quality of nectar, body size and tongue length of pollinators, floral shape, size and colour are known to cause orientation in honey bees to locate food source of their choice. Honey bees have certain idiosyncrasies which are very useful for pollination point of view and generally increase their efficiency as pollinators (Free, 1993). Honey bees are known to be “fairly faithful” and “constant” to plants and become “fixed” to small area of crops being worked by them for collecting nectar and pollens. The blossoms of onion crop are highly attractive to pollen and nectar collecting insects. The receptivity of stigma within one to two days, provides better chance to the plant to get pollinated by insects (Baswana, 1984). Higher seed yield of the crops may be obtained by the maintenance of a large population of pollinating insects due to visit by a large number of pollinating species to the crop (Sihag, 1985, 1986; Free, 1993; Singh and Hameed, 1995). Honey bees are considered as the primary agents for pollination in onion crop (Walsh, 1965). Rao and Lazer (1980) gave major credit to the honey bee as a pollinator of onions, however, Halictus farinosus and Osmia rufa was found to be the most abundant pollinator of onion by Parker (1982) and Wilkaniec et al. (2002), respectively. On Allium sp., the dominance of the giant bee A. dorsata as efficient pollinator was recorded by many workers (Chaudhary, 2004; Shafqat and Masood, 2008). Jadhav (1981) also reported that A. florea is the most important pollinator for onion var. N-53. A. cerana was considered as more efficient pollinator by Rao and Suryanarayana (1989) on the basis of visiting more number of florets and umbels in a unit time than A. florea and Trigona iridipennis. Among the pollinators, A. dorsata was found to be a predominant visitor covering an average of 7.5 flowers per umbel per visit during peak hours of their foraging activity (1200-1400 h) followed by A. cerana (5.4 flower/umbel/visit) ascompeared to A. florea, A. mellifera and syrphid flies (Chandel et al., 2004). In the same study, Syrphids covered a minimum of 1.6 flowers/umbel/visit, yet spent maximum time (8.8 seconds) on the flowers during 800-1200 hours. Apis dorsata had the maximum foraging period (0630-1855 h) followed by A. cerana (0645-1830 h) and A. mellifera had the least foraging period (0725-1820 h) on onion seed crop. In contrast to previous report where A. cerana was considered as second most abundant pollinator, Chaudhary and Sihag (2003) reported A. florea as the second most abundant species on onion after A. dorsata. According to Witter and Blochtein (2003), A. mellifera transported more than 70 percent of pollen and become indispensable in onion pollination.
Effect of nectar on foraging behavior: The foraging activity of honey bees on onion inflorescences is dependent on the interactions of several factors like nectar quality, sugar quantity, potassium content etc. Waller (1970) believed that a high level of potassium in the nectar might be an important clue to the reluctance of bees to visit onion flowers. Jula et al. (1965) calculated that onions produced 71 percent as much nectar per day as the highly attractive saffoinf. Similarly, Silva and Dean (2000) observed that in nine inbred lines of onion (A. cepa), the average amount of nectar produced by umbels and the individual florets were significantly positively correlated with the number of bee visits. The mean number of honey bees visiting on inflorescence every ten minutes and the mean residing time of each honey bee on a seed stalk were significantly different among the cultivars. Hurand flowers of onion had the least number of visitors and Dorche flowers had the longest visiting time (Seyedebrahim et al., 2004).

Nectar is recognized as the main attractant for pollinators. Many workers have worked out a linear relationship between the quantity and quality of nectar and population of honey bees (Wykes, 1953; Mommers, 1977; Corbet, 1978). Hagler et al. (1990) examined nectar characteristics of six onion varieties and recorded that mean nectar amount ranged from 0.54 to 0.84 µl per day. Mohr and Jay (1990) found that mean daily nectar production and sugar concentration for Brassica compestris cultivars were 0.68 µl and 57 per cent respectively and for B. napus cultivars were 0.90 µl and 62 per cent respectively. The major sugar constituents of various nectar types are sucrose, glucose and fructose (Wykes, 1952). Generally, pollinators with high energy requirements foraged on sucrose rich flowers, whereas those with low energy requirements relied on glucose or fructose rich flowers (Abrol and Kapil, 1991).

Nectar sugar concentration is one of the most important factors affecting bee flower interaction. A positive correlation was found between attractiveness to bees and nectar sugar concentration in citrus, suggesting that this characteristic is one of the parameters responsible for variability in attractiveness to honey bees (Wolf et al., 1999). Generally high nectar sugar concentration was desirable for attracting the honey bees (Frisch, 1950; Meloyan 1975). Frisch (1950) reported the threshold value (5 to 40%) of sugar concentration for its acceptance by the bees. Backman and Waller (1971) observed that the bees rejected a solution with sugar concentration less than 20 per cent. It has also been reported that honey bees were able to discriminate a sugar solution with a difference of 5 per cent concentration (Jamieson and Austin, 1956). Various workers in variety of plant species recorded floral nectar sugar concentration ranging between 4-87 per cent (Vansell, 1934; Fahn, 1949 and Percival, 1965). Some of the species reported by Shuel (1955) having remarkable high concentration of sugar are Astragalus pachypus (59.2%), Salix sp. (60%) Robinia pseudo-acacia (63%) Aesculus sp. (72.2%) and Vitis sp. (75%). Geger and Thompson (2004) observed a strong positive relationship between degree of flower constancy and rate of net energy gain indicating that honey bees were more economic foragers. Abrol (2006) observed a significant positive correlation between bee activity and nectar sugar concentration.

Foraging activity: The density of insects on blossom depends on several factors like flower shape, size, colour, availability of floral rewards and weather conditions (Mevett et al., 1989). Insect pollinators have their specific ecological threshold level, below which activity does not occur. The ecological threshold required for normal activity and its maintenance differ inter- and intra- specifically depending upon the level of adaptability of a species in a given environment (Kapil and Jain, 1980). Insect activity increases sharply after sunshine, decreases gradually through the day and ceases before sunset (Oh and Woo, 1990). The daily flight activity varies with the time of the day and meteorological variables, especially wind, rainfall, temperature and humidity (Sarviva, 1985). Bees collect pollen on cucumber in early morning and switch to nectar later in the morning. The first honey bee to visit a flower coats a large portion of the stigma with pollen. Although there is less receptive surface on the stigma with each succeeding visit but multiple bee visits per flower (within the range of 1-20) increase fruit-set and average number of seeds per fruit (Collison, 1976). In general, when bees start foraging they might collect nectar and/or pollen (Crane, 1990). Many bees that collect pollens change later in to the nectar, but once the bees start collecting nectar are unlikely to change to pollen collection. Flower visitors seem to prefer nectar collection even if it takes them much longer time to get nectar. Honey bees collected nectar from both stamine (S) and pistillate (P) flowers but few bees collected pollens. Bees spent twice as long on ‘P’ flower as on ‘S’ flower (Collison, 1973). Nemirovich-Danchenko (1964) observed that nectar secretion was greatest after 3 to 4 hours of the flower opening. Amaral et al. (1963) concluded that bees show no preference for stamine over pistillate flowers. Bees work on blossoms later in the day in springtime or in cooler climates than in summer or warmer climates.

McGregor (1976) showed that A. mellifera was active between 0900-1300 h on onion umbels and collected heavy pollen loads during morning and at noon. Ewies and
El-Sahhar (1977) recorded 1100-1400 h as the most active period of the day for bee visitation on onion. According to Jadhav (1981), A. florea started foraging activity a little earlier (0855 h) than A. dorsata (0930 h) and continued late hours in the evening (1700 h) as compared to A. dorsata which stopped the day’s work at about 1625 h. Yucel and Duman (2005) observed that A. mellifera foraged on onion umbels between 0815 to 1630 h and peak foraging was between 1100-1200 h.

Foraging speed and rate: Foraging speed (time spent per flower) and foraging rate (number of flowers visited per min.) depend upon the foraging behaviour of insects and floral structure of the crop concerned, particularly the corolla depth (Gilbert, 1980). Foraging is a trade between the amount of nectar expected from a flower and time required to extract it (Pyke et al., 1977). Inouye (1980) observed that more the nectar is available, more time will be spent per flower however, both the parameters might be affected by the length of proboscis (Inouye, 1980). The number of flowers visited by an insect species also depends upon the type of floral reward (working for nectar and/or pollen), bloom and the density of flowers on a particular cultivar.

Foraging speed of the insect depends upon the foraging behaviour of the visitors and floral structure of the crop (Free, 1993). Foraging speed varies among the insect species. Apis cerana indica nectar foragers, visited 17.5 and 25.0 flowers per minute in the morning and afternoon, whereas, A. mellifera visited 25.8 and 33.6 flowers per minute during the same hours (Gupta et al., 1984). Weather conditions have a pronounced effect on foraging speed of insects. Generally, adverse whether conditions increased the time spent per flower. Ideal conditions for bee-flying include temperature greater than 21°C (70°F), humidity less than 75 per cent, wind speed below 25 km/h (15 mph) and few or no clouds (Meléndez-Ramirez et al., 2002). Foraging rate of foragers is influenced by the length of corolla tube apart from a complex system of factors like temperature, humidity etc. (Benedek, 1976). Rate of foraging by an individual bee increases when the bee finds profitable flower patch (major nectar source) but declines when the individual bee assess low profitability from its forages (Seeley et al., 1991).

According to Ewies and El-Sahhar (1977), 2.6 bees/ min visited one umbel with 6.8 movements between the florets of an umbel. In another study, onion umbels received an average of 0.6 A. cerana bees/ min. and time spent by a bee on a flower was 3.3 seconds (Kumar et al., 1989). Rao and Suryanarayana (1989) observed that A. cerana, and A. florea initiated foraging at 0950-1130 h and ceased foraging at 1710-1815 h. Chaudhary (2004) reported that A. dorsata and A. florea started their activity in the morning (0700-0800h) and remained active till evening (1800h). Yucel and Duman (2005) recorded that A. mellifera visited 8, 13 and 4 flowers per minute at 0900, 1200 and 1500 h and collected 8, 10 and 6 mg pollen from onion umbels. According to Shafqat and Masood (2008), Eupeodes corollae (Syrphidae) exhibited the most efficient foraging behaviour by visiting 17.1± 1.38 flowers in 147.5± 8.14 seconds on an umbel. Saeed et al. (2008) recorded that honey bees began foraging on A. fistulosum flowers at about 0600 h and ceased at about 1900 h with a total foraging activity time of 1300 h which was slightly more than the time recorded in the present study (1130 h for A. dorsata).

Loose pollen grains sticking to the body of a bee: The honey bee becomes well dusted with pollen grains as a result of inserting their heads into the middle of the staminal column of a flower and curling their abdomen around anthers, thus, they carry more pollen grains. Amount of loose pollen on the body varies with the plant species and the varieties of a crop on which the insects are visiting. Furthermore, solitary bees have the advantage of carrying it in a drier condition, which is more likely to be rubbed off easily in to the stigmas of the flowers (Free, 1960). The amount of loose pollen grains on the body of an insect varies on different body parts. Usually, it may be twice on bee’s thorax as on its abdomen. While working over flowers, pubescent hairs on their bodies may entangle as many as 25000 to 300000 pollen grains (Skrebtsova, 1957). While visiting various flowers of the same plant species honey bees are instrumental in disseminating pollen and consequently accomplish the job of pollination par excellence.

In cucumber, honey bees exhibit no preference for staminate vs. pistillate flowers (Stephen, 1970), while Collison and Martin (1979) reported that the staminate flowers of cucumber were relatively more attractive than pistillate and this might be related to higher sugar concentration found in the nectar of staminate flower. The amount of pollen carried on insect bodies and their viability was influenced by the onion cultivar and the visitor species (Parker, 1982). Richard et al. (2003) reported that the behavior of nectar foragers on staminate flowers differed according to body size. Large bees foraged for nectar mostly in the afternoon after nectar sugar concentrations reached high values, while smaller bees foraged for nectar throughout the day.

Sharma and Singh (2000) reported that the number of loose pollen grains sticking on an individual bee of two species, while foraging on sunflower head was counted to be 22900 and 20500 for A. dorsata and A. mellifera, respectively.
at Hisar. Similarly, Kumar (2002) observed that the number of sunflower loose pollen grains sticking on the body surface of *A. dorsata* was maximum (111109.40 during April 2002 and 90623.45 during May 2002) followed by *A. mellifera* (74998.45 during April 2002 and 72917.70 during May 2002). Hence, it was concluded that *A. dorsata* was most efficient carrier of the loose pollen grains. Sharma and Singh (1999) reported that *A. dorsata* carried more number of carrot pollen grains (av. 5200) than *A. florea* (av. 4700). The number of pollen grains sticking to the body of different bee species, while foraging *Brassica campestris* bloom was 13187, 4857 and 11437 on *A. dorsata*, *A. florea* and *A. mellifera*, respectively (Sharma et al., 2000). Gill et al. (2001) stated that the number of loose pollen grains sticking on an individual bee of three species while foraging on phalsa flowers were counted to be 6901.5 in case of *A. dorsata* followed by 5506.3 and 4710.9 pollen grains in *A. mellifera* and *A. florea*, respectively. The number of loose pollen grains sticking on an individual bees of two species while foraging on onion flowers were counted to be 10187 (*A. dorsata*) and 5625 (*A. florea*) at Hisar (Sharma et al., 2001).

Pollination efficiency: Pollination efficiency of different insect pollinators has been evaluated on the basis of number of characteristics. Most of the workers (McGregor, 1976) considered the relative effectiveness in the variability of various species to affect pollination in spite of their abundance (Anderson et al., 1982). Therefore, the efficiency of an insect species as a pollinator has also been attributed to its size, foraging behaviour and the amount of loose pollen grains adhering to its body (Free et al., 1975). Brantjes and Leemans (1976) considered that large sized insects were effective in pollination of flowers due to their body contact with anthers and stigmas as compared to small size insects, which often missed their contact with anthers and stigmas while foraging for floral rewards. Therefore, different characteristics can be combined to determine the pollinating efficiency of insect visitors/ *Apis* spp. on the basis of actual field observations on abundance, their foraging behaviour, siliqua and seed set in *B. campestris* var. sarsonflowers, which were allowed one visit by an *Apis* sp. and by using all these parameters for developing an equation. Based on size, hairiness, activity pattern and quantity of loose pollen grains carried by different pollinators, these are assigned pollinators' efficiency rating. This efficiency rating is multiplied by the number of insects concerned that are foraging on the crop (relative abundance) to give relative pollination index for the species. For honey and bumble bees, it is essential to take into account the proportion of nectar and/or pollen gatherers and the proportion that obtain forage without pollinating the flowers (nectar robbers or side workers). This is considered to be the most reliable method for computing pollination efficiency of insect visitors on different crops.

Insects visit the flower of commercial crops to seek nectar and/or pollen and contribute in pollination. The absolute necessity of insect pollination on fruit set in non-parthenocarpic cucumber varieties as there was 100 per cent abortion for all pistillate flowers that received no entomophilous visitation were demonstrated. Total abortion of female flowers in the absence of bee visitation found in these experiments confirms the results of other studies on cucumber (Morris, 1968). However, relatively a few are consistently good pollinators. The different criteria to be used for evaluating the relative efficiency of insect visitors are abundance, foraging behaviour, loose pollen carrying capacities, multiplicities of bee visits and morphometrical characters, i.e., body size, tongue length, pollen collecting apparatus and hairyness. Various workers (Free, 1993) considered the relative effectiveness of insect pollinators of crops on the basis of their abundance alone. However, there are inherent differences in the ability of various species to affect pollination inspite of their abundance (Anderson et al., 1982). Therefore, efficiency of an insect as a pollinator has also been attributed to its size, foraging behaviour and the amount of loose pollen grains adhering to its body (Free et al., 1975). Baker et al. (1971) reported that the frequency of flower visitors, the number of flower visited per unit time, the amount of pollen picked per visit helped to distinguish the pollinators as major and minor ones.

Kumar (2002) reported that *Melissodes* sp. was found to be the best pollinator of cucumber blossoms. The *Sarcophaga* sp. and *A. mellifera* were ranked second and third. Bumble bees (*Bombus impatiens*) visited flowers consistently had a lower percent abortion than honey bees (*A. mellifera*) when compared at equal bee visit numbers (Stanghellini et al., 1997). Use of bees increased the productivity of hybrids Maiskii, TSKhA-1 and TSKhA-77 by 34.7, 50.0 and 21.2%, respectively (Kochetov, 2004). In watermelon, the anthesis in both staminate and pistillate flowers took place in early morning (0600 h) and flowering lasts for 6-9 h. *Apis cerana* (87%) was the principal pollinating insect at Vijayarai and was found to be more efficient pollinator than *A. florea* and *Trigona irridipennis*. *Apis cerana* population was maximum at 0900 h; also during the period, the maximum pollen collectors were found at Andhra Pradesh (Rao and Suryanarayana, 1988).

The pollination efficiency of three honey bee species *A. dorsata*, *A. florea* and *A. mellifera* on phalsa flowers under semi-arid subtropical conditions of Haryana showed that the
abundance of *A. florea* was maximum (4.88 bees/branch/5 minute) than abundance of *A. dorsata* and *A. mellifera* was 2.70 and 0.96 bees/branch/5 minute, respectively (Gill et al., 2001). The number of loose pollen grains sticking on *A. dorsata*, *A. mellifera* and *A. florea* were 6901.5, 5506.3 and 4710.9, respectively. On the basis of pollination index, *A. florea* was found to be the most efficient pollinator (22989.2) of this crop followed by *A. dorsata* and *A. mellifera* with a pollination index of 18634.0 and 2286.0, respectively (Gill et al., 2001). Sharma et al. (2000) observed that *A. dorsata* was the most efficient pollinator followed by *A. mellifera* and *A. florea* on ‘sarson’ bloom. Similarly, *A. dorsata*, having a pollination index 162247 was found to be the most efficient pollinator of sunflower than *A. mellifera* having a pollination index of 124066 at Hisar (Sharma and Singh, 2000). In onion, among different insect visitors, *A. cerana indica* was the most dominant (68.30%) followed by *T. irridipenis* (46.66%) and *A. florea* (42.73%) (Rao and Lazer, 1980). However, Sharma et al. (2001) reported that on the basis of pollination index, *A. dorsata*, having a pollination index of 12082 was found to be the most efficient pollinator of onion crop under agro-ecological conditions of Hisar than *A. florea* having pollination index of 4298. *A. dorsata* is bigger in size and has more number of body hairs than *A. florea*, which is smaller in size and consequently has less number of body hairs. Therefore, *A. dorsata* entrapped more number of onion loose pollen grains on the body as compared to *A. florea*.

**Effect of meteorological variables on foraging behavior:** Each honey bee species was found to have its specific ecological threshold below which activity does not occur. Available literature on the effect of environmental factors in influencing the foraging pattern of various pollinators suggests that temperature plays a key role in initiation and cessation of foraging activity. Kapil and Kumar (1974) reported 15–18°C as the minimum threshold temperature for commencement of field activities in honey bees. In a similar study, Osgood (1974) reported that ambient temperature is the predominant factor governing the morning flight of *Megachile rotundata* while cessation of activity is governed by light intensity. Szabo and Smith (1972) reported that greatest foraging activity of *M. rotundata* occurred at 30°C in bright sunshine and declined at higher temperature in Hungary. Kapil and Brar (1971) recorded peak activity of *A. florea* on toria between 21–25°C temperature and 50–57 per cent relative humidity during November. In general, suitability of optimum bee activity varies from season to season, depending upon the geographical regions, time of the year, other melliferous crops or other species of bees.

Several other workers also reported that air temperature significantly affected the foraging activities of honey bees as flower visiting rate was increased with increasing air temperature. Kwon and Saeed (2003) also highlighted the importance of temperature on the foraging activity of *Bombus terrestris*. L. Nuenz (1977) reported that morning activity of *A. mellifera* was related to nectar flow, and afternoon activity with photoperiod. Gary (1975) stated that 13°C appeared to be the minimum threshold temperature for initiation of the field activities by the honey bees which continued at extremely high temperature of 43°C for water collection but at this temperature nectar and pollen foraging was ceased. Whitcomb (1980) reported that *A. florea* worker bee did not forage at temperature below 18°C. Jain and Kapil (1980) reported that air temperature appeared to be a key factor influencing the initiation of bee activity but cessation was independent of air temperature. Alam et al. (1987) observed that honey bee activity was highest when the temperature averaged from 31.8° to 34.9°C; thereafter, foraging activity of honey bees declined as temperature increased and did not resume again in favourable temperature in the evening. It was postulated that availability of pollen and nectar are crucial for foraging activity on a particular crop.

Bee activity was found to be uniformly positively and significantly correlated with the ambient temperature and nectar sugar concentration on all the cultivars of oilseed crops (Sihag and Khatkar, 1999). The correlation coefficient matrix between bee activity and environmental factors indicated that foraging populations of *A. dorsata*, *A. mellifera*, *A. cerana* and *A. florea* correlated significantly and positively with air temperature (Abrol, 2006).

In majority of the studies, foraging activity was also found to be significantly and positively correlated with solar radiation intensity (Abrol, 2006). Lerer et al. (1982) stated that though ambient temperature plays an important role in the initiation of flight and hence in the pollination activity of *M. rotundata*, but it is the solar irradiance that appears primarily responsible for controlling the pollination activity. Cessation of activity occurred even before the temperature dropped to the level required for initiation of bee activity. The correlation coefficient matrix between foraging populations of honey bees (*A. dorsata*, *A. mellifera*, *A. cerana* and *A. florea*) and solar radiation and light intensity was significantly and positive (Abrol, 2006).

In earlier studies, foraging activity of honey bee species was also found to be significantly and negatively correlated with relative humidity (Sihag and Khatkar, 1999). Jain and Kapil (1980) reported that the suitability of
atmospheric temperature coupled with relative humidity and light intensity not only favoured the initiation but also led to maximum of bee activity. In the evening and relative humidity remained favourable but cessation of bee activity occurred due to decline in the light intensity. However, Burill and Dietz (1981) found that in honey bees, foraging activity increased with increasing air temperature but was not correlated with changes in atmospheric pressure and relative humidity.

In most of the studies combination of various meteorological parameters were found to govern the foraging pattern of pollinators. Kapil and Brar (1971) stated that a combination of 15-18°C temperature and 80-82 percent RH appeared to be minimum activity peaked at a combination of 22-25°C temperature and 50-65 percent RH. The cessation of activity seemed to be governed by the fast decline in light intensity. Similar results were obtained by Cirudarescu (1971) who found that the number of insect visitors on lucerne varied directly with temperature and inversely with relative humidity. Sihag (1984) gave a conclusive report that in social bees temperature acted as a stimulus for the commencement and cessation of pollination activity in winter whereas light did it in summer. Winter solitary bees behaved identically alike which social bee did in winter. However, in summer solitary bees, for the commencement of foraging activity, increasing temperature in the morning acted as a stimulus, whereas, cessation in the evening was affected by decreasing light intensity.

Abrol (2006) studied various meteorological parameters in detail in relation with foraging activity of pollinators. For initiation of flight activity A. dorsata required 16°C temperature, 74 % relative humidity, 600 lx light intensity and 10 mW/cm² solar radiation; A. mellifera required 16°C temperature, 75 % relative humidity, 800 1x light intensity and 10 mW/cm² solar radiation; A. cerana required 15.5°C temperature, 76 % relative humidity, 600 1x light intensity and 9 mW/cm² solar radiation and A. florea required 18.5°C temperature, 64 % relative humidity, 1700 1x light intensity and 20 mW/cm² solar radiation (Abrol, 2006). Thereafter, all honey bee species continued foraging under light intensity, solar radiation and temperature levels lower than conditions needed to commence foraging. However, cessation of foraging activity occurred even before temperatures dropped to the values required for commencement of field activity.

Additionally, peak of anthesis also governed the foraging pattern of various pollinators. The most common visitors were the honey bees (A. florea and A. dorsata) which were most active about 1100 to 1400h; the peak of anthesis also occurred during this period (Baswana, 1984). Pollen foragers started their activity at 0845 to 0915h on coriander blossom and stopped at 1600 to 1700h (Shelar and Suryanarayana, 1981).

However, workers have highlighted the importance of other factors in regulating the flight activity of bees. For instance, Belluscì and Marques (2001) reported the importance of circadian activity rhythm of the foragers of a eusocial bee, Scaptotrigona sp. outside the nest. In a similar study, Harrison and Fewell (2002) found that environmental and genetic influences regulate the flight metabolic rate in the honey bee, A. mellifera. Higher air temperatures tend to increase colonial net gain rates, efficiencies and honey storage rates due to lower metabolic rates during flight and in the hive. They further found that variation in flight metabolism has a clear genetic basis. Different genetic strains of honey bees often differ in flight metabolic rate, and these differences in flight physiology can be correlated with foraging effort, suggesting a possible pathway for selection effects on flight metabolism. Pereboom and Biesmeijer (2003) on the other hand emphasized more the importance of body size and coloration for stingless bee foragers. Devillers et al. (2004) reported on modeling the flight activity of A. mellifera at the hive entrance.

Theoretical and empirical models to study foraging behaviour: Pollinator-plant interaction has co-evolved as reciprocal selective factors shaping the behaviour, physiology and ecology of each other. In the course of evolution, there has been a competition between the plants for pollinators and between the pollinators for plants (Heinrich and Raven, 1972). In later years, the “energetics” approach has been a major focus of behavioural ecologists for studying foraging behaviour of insect visitors of flowering plants (Schmid-Hempel, 1984). Heinrich and Raven (1972) emphasized the role of energetics in flower foraging and in the evolution of bee flower relationship. The food rewards from a plant species is the quantity of food that can be collected per unit time. This quantity is a function of the distance between flowers and the speed with which food rewards can be gathered from them. Acquisition of energy rewards comes only with the costs. Time and energy are spent during all foraging activities. The rate at which flowers can be manipulated makes the difference between profit and loss. Flowers have different structure that require different pattern to be learned through trial and error for acquiring food. All this information is used to choose between flowers of different species and to make foraging decisions. MacArthur and Pianka (1966) developed a theoretical and empirical construct, the optimal foraging theory (OFT), which lead to a better understanding of foraging behavior. Emlen (1966) demonstrated the need for a model
where food item selection of animals could be understood as an evolutionary construct which maximizes the net energy gained per unit feeding time. Optimal foraging theory (Waddington, 1982) hypothesizes animals will forage in ways that maximized some measure of foraging efficiency. The "currency" (Schoener, 1971) usually thought to be maximized is net rate of energy intake although other possibilities exist (Pyke et al., 1977). Natural selection is expected to favor efficient foraging patterns and this expectation forms the basis of a large body of optimal foraging theory.

Effect of mode of pollination on crop yield parameters: Honey bees are the most important pollinators of onion crop because the duration of pollinator visits to a flower is correlated positively to pollination rate, which is itself correlated to the number of seeds produced, their weight and their seedling length. Van der Meer and van Bennekom (1968) reported only 9 percent self-fertilization in onion crop which corroborated the present finding of low seed set in self pollination. In Poland, the yield of hybrid seed of plants in field cages pollinated by honey bees, bumble bees (Bombus terrestris or B. ruderarius) and Megachile rotundata was equivalent to 301, 295 and 47 kg/ha, respectively (Ruszkowsk and Bilinski, 1984). In a similar study, seed set (68.8%) and germination (86%) in onion seeds was better in open pollination as compared to self pollination (22.8, 67.5%, respectively) (Kumar et al., 1985). They although reported higher seed set and germination in open pollination in onion than in caged umbels but no significant difference was observed between these treatments for mean weight of 100 seeds.

Nogueira-Couto and Calmona (1993) grew cucumber plants with three different treatments, i.e., netted without honey bees, netted with honey bees and open-pollinated produced. They observed that open pollinated plants produced more fruits than without pollination. Cervancia and Bergonia (1991) found that per cent fruit set of bee-pollinated and open-pollinated (uncaged) plants did not differ significantly in Philippines, but was about twice that of non-pollinated plants. They further observed that fruits were heavier (0.87 kg) and more uniform than those of open-pollinated plants (0.6 kg), while fruits from non-pollinated plants were shortest and lightest (0.36 kg). The percent fruit set was maximum (84.29%) under bee pollination plus hand pollination and minimum (79.9%) under hand pollination conditions. Average fruit diameter, fruit length and fruit weight was maximum (3.51 cm, 13.31 cm and 135.25 g, respectively) under bee pollination and bee pollination + hand pollination, while these were observed minimum (3.49 cm, 12.19 cm and 132.83 g, respectively) under hand pollination conditions (Kumar, 2004).

In onion crop, Glukhov (1955) and Martin (1979) observed higher germination (97%) and emergence rate (85.5%) in open plots as compared to caged plots (85.5 and 81%). Gjorgji and Rukie (1997) revealed that seed germination rate was 3.6 per cent greater in onion with honey bee activity. Yu et al. (1998) recorded that rates of seed set were high (64.1%) in fly pollinated onions as compared to 62.7 and 60.8 per cent seed set in honey bee pollinated and open pollinated crop. Munavar and Muzaffar (1999) recorded 10-11 fold increase in seed yield due to honey bee pollination. Yucel and Duman (2005) reported that seed yield per bulb was higher in open plots (5.74 g/flower) as compared to 1.29 g/flower in caged plots. A. dorsata was revealed as the most effective pollinator based on seed setting results which produced 506 seeds/umbel/20 minute visit (Shafqat and Masood, 2008).

Effect of honey bee pollination on crop yield parameters: Effect of honey bee pollination was studied in comparison with other modes of pollination in various crops including onion. Hamilton (1946) found that an onion grower produced more seed than he had in the past after he rented 8 colonies of bees. Sanduleac (1961) and Le Baron (1962) stated that bees increase eight to ten times the production of onion seed in Romania, and recommended about two colonies per acre. Jones and Emsweller (1933) reported 157 seeds produced per bagged head compared with 712 seeds in open pollination. The increase in seed production was found to 175 (Deodikar and Suryanarayana, 1972) to 1000 per cent (Singh and Dharamwal, 1970) under bee pollinated area. Although Nye et al. (1971) reported an average of 100 bees per 100 feet of male fertile rows and a maximum of 40 per 100 feet on the male sterile rows, the number of honey bee visitors needed per onion plant, umbel, or linear feet of row has not been determined. The study conducted by Benedak and Gaal (1972) revealed that fertilization rate, seed yield and percentage of germination were significantly better in uncaged inflorescences. Singh and Dharamwal (1970) reported an increase of 72-79 per cent in seed set in open pollinated plants over bagged plants and Jadhav (1981) recorded per cent fruit set and seed number were 74.33 and 1063 in open pollination with better seed germination (90.7%) as compared to 7.67 per cent fruit set and 49 seeds in bagged umbels. El-Sahhar (1977) reported 61.8 per cent seed setting in open pollination as compared to 1.5 per cent in self pollination of onion crop. Woyke (1981) observed that numbers and weight of onion seeds from self pollination were very low as compared with yields on open fields provided with honey bee colonies.
The pollination by honey bee, A. cerana and by hand gave 15 and 8 per cent fruit set in bottle gourd, respectively, whereas, isolated plants gave only 3-5 per cent fruit set in Punjab (Alam and Quadir, 1986). Kutty and Rovelio (1992) reported that honey bee pollination produced more fruits per plant, higher seed weight and greater seed viability than hand pollination in melon. Under honey bee pollination, more than 85 per cent of flowers set fruit, compared with less than 20 per cent for hand pollination. Brewer (1974) reported that the weight of melons and both number and weight of mature seeds per melon were significantly higher from plots visited by bees than those where bees were excluded in Colorado (USA). Nogueira-Couto and Calmona (1993) observed that cucumber plots netted with bees yielded more fruits/m² and heavier and higher quality fruits than other plots. The weight of fruits on an average was 2.73 kg per plant visited by insect pollinators and 1.9 kg per plant not visited by bees indicating more than 30 per cent higher fruit yield by pollination. Munavar and Muzaffar (1999) recorded 10-11 fold increase in seed yield due to honey bee pollination. The seeds from induced bee pollination showed high seed set (Prasad et al., 2000), maximum germination (Chandel et al., 2004), shoot and root length (Kalmath and Sattigi, 2004) as compared to control. Onion (Allium cepa L.) does not produce quality seed if insects do not visit the flowers. In mountainous regions of India, availability of natural pollinators has been a major drawback in seed production (Chandel et al., 2004). According to Chandel et al. (2004), induced bee pollination increased seed yield by 2.5 times and produced on an average 971 seeds per umbel compared to 406 in the control. The seeds from induced pollination field resulted in 90 percent germination compared to 69.5 percent germination from the control. Yucel and Duman (2005) reported that seed yield per bulb was higher in open plots (5.74 g/flower) as compared to 1.29 g/flower in caged plots. A. dorsata was revealed as the most effective pollinator based on seed setting results which produced 506 seeds/umbel/20 minute visit (Shafqat and Masood, 2008).

Several pollination factors are considered for agricultural production such as self-pollination, wind pollination, hand pollination, pollen dispensers, pollination through insects, birds etc. Vegetable and fruit crops depend upon insect pollination for yield and fruit quality. Colour, shape and odour of flowers are well-known attractants to pollinators. Besides these physical features, the other source of variation for differential attraction between genotypes is the caloric reward viz., nectar and pollen provided by the flowers. Different cultivars differ in their production of pollen and bees can discriminate these varieties. Likewise, the nectar provided by the flowers has been found to be a significant parameter that shapes the behaviour of pollinators in relation to their energetic needs.

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