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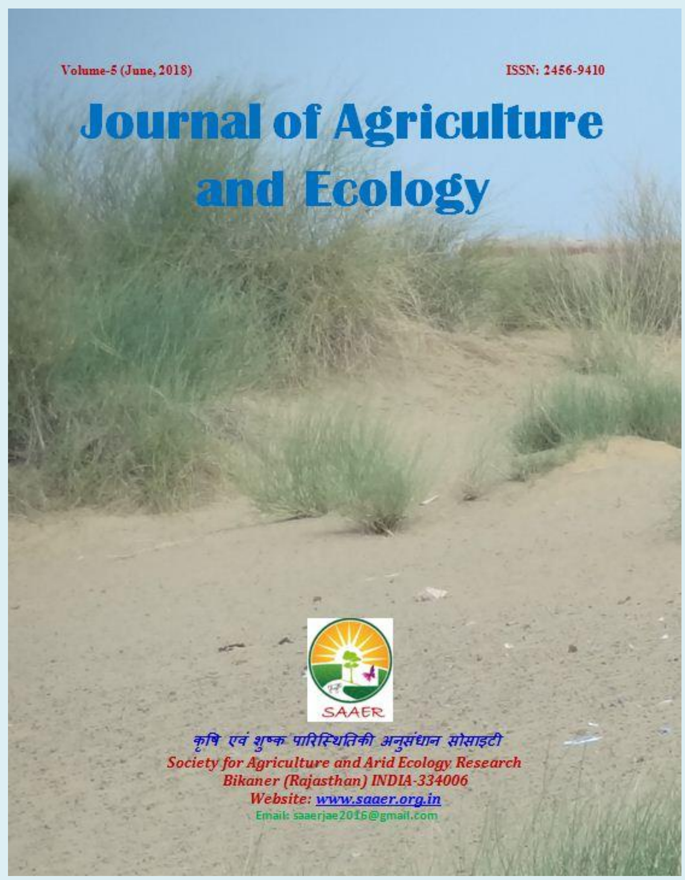

Journal of Agriculture and Ecology

ISSN: 2456-9410
Volume: 5

Journal of Agriculture and Ecology (2018) 5: 1-25

Journal of Agriculture and Ecology, 2018, Vol.5, 1-25
http://saaer.org.in

Review Article **Open Access**

Role of insect pollinators and pollinizers in arid and semi-arid horticultural crops

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Article Info

Article history
Received: 10 February 2018
Accepted: 20 May 2018
Available online: 15 June 2018

Key Words: Pollinator, pollinizers, honey bee, arid and semi-arid horticultural crops.

Abstract

Pollinators and pollinizers play pivotal role in pollination of arid and semi-arid horticultural crop species for sustaining the crop diversity and production systems. Many horticultural crops such as ber, aonla, pomegranate, phalsa, fig, jamun, citrus, bael, khejri, cucurbits, field beans etc. require insect pollinators for efficient pollination) to gain the higher yield. The pollinators and pollinizers increase quantitative and qualitative traits of horticultural crop produce. The present paper provides comprehensive information on the role of native as well as managed pollinators in the arid and semi-arid horticultural crop production. It is necessary to understand the importance of pollinators and pollinizers species richness or diversity in their natural habitat and role in crop improvement. The pollination with honeybees, knowledge about pollinizers, pollinator's management and artificial pollination are major horticultural inventions to enhance the yield and quality in horticultural crops, since they are highly cross pollinated crops, and promote beekeeping industry to produce good quality honey.

Preferred citation: Haldhar SM, Kumar R, Samadia DK ,Singh B & Singh H. 2018. Role of insect pollinators and pollinizers in arid and semi-arid horticultural crops. *Journal of Agriculture and Ecology*, 5: 1-25.

Introduction

Pollination is a major phenomenon in flowering plants including horticultural crops which determine fruit set intensity and production efficiency. It involves effective integration of pollinator and pollinizer through varietal compatibility, synchronous blooming and favorable environmental conditions. A pollinator is a biotic agent that moves pollen from anther to the stigma of flower which leads to the development of fruits or seeds through fertilization. The pollinators include bees, flies, bats, moths, or birds. On the other hand, a pollinizer is the plant that serves as the pollen source for related plants for effective fertilization. Many horticultural crops are actually self-sterile and require cross-pollination to produce seeds and fruit (McGregor 1976; Free 1993). Some plants are self-fertile and can pollinate and fertilize themselves. A good pollinizer is a plant that provides compatible, viable and plentiful pollen and blooms at the same time of plant that to be pollinated and its pollen can be stored to pollinate the desired flowers in future. Hybridization requires cross pollination between flowers of different species or between different breeding lines or genotypes for varietal improvement. The first fossil record for biotic pollination is from fern plant of Gymnosperms which showed the evidence for biotic pollination in early Triassic period. Many fossilized pollens showed similar morphological characteristics to biotically dispersed pollen in the present era. Studies of pollination have a long history that extended way back to the Greek philosopher, Theophrastus (around 320 BC), who described the complex pollination mechanism in the fig plant. The contributions by Charles Darwin on pollination in orchids (Darwin 1862) and reproduction in plants (Darwin 1876) perhaps formed the starting point for present-day scientific studies on pollination. The interaction between flowering plants and pollinating insects is a mutualism where the plants dispersed their reproductive gametes (pollen grains) by insects, and the insects are rewarded with nectar and pollen. The relationship between beetles and angiosperms during the early Cretaceous period led to parallel radiations of angiosperms and insects into the late Cretaceous era. The evolution of insect nectars in late Cretaceous period that time flowers signals of the mutualism between hymenopterans and angiosperms. Insects plays important role as pollinators of wild plants and several crop species. Pollination by animals is an important ecosystem service because crop plants accounting for 35 percent of global crop based food production benefit from animal mediated pollination. Approximately 75% of the crops cultivated worldwide depend upon pollinators to produce seeds, fruits and vegetables (Delaplane & Mayer 2000) which promote either yield quantity or quality for crops (Morandin & Winston 2006; Klatt et al. 2014; Pashte & Kulkarni 2015; Singh et al. 2016). An insect cannot be considered a pollinator if it visits a flower and does not touch the reproductive parts, does not carry pollen or carries nonviable pollen, or visits the flowers when the stigma is not receptive (Dafni et al. 2005). However, many insects can collect floral resources from cucurbits without touching the reproductive parts of flowers or only occasionally visit flowers and contribute nothing or very little to the pollination process.

Among insects such as bees, flies, beetles, butterflies, midges, moths, wasps, and weevils are important pollinators of many crops. Agricultural and horticultural crops including forage crops, ornamental plants, and wild plants are effectively pollinated by insects by mean of transfer of nectar or pollen from one flower to another flower. Among the total pollination activities, over 80 per cent are performed by insects. Honeybees are critically important for crop pollination worldwide (Thapa 2006; Klein et al. 2007).The yields of some fruit, seed and nut crops can decrease by more than 90 per cent without honeybee

Journal of Agriculture and Ecology, 2018, Vol.5, 1-25
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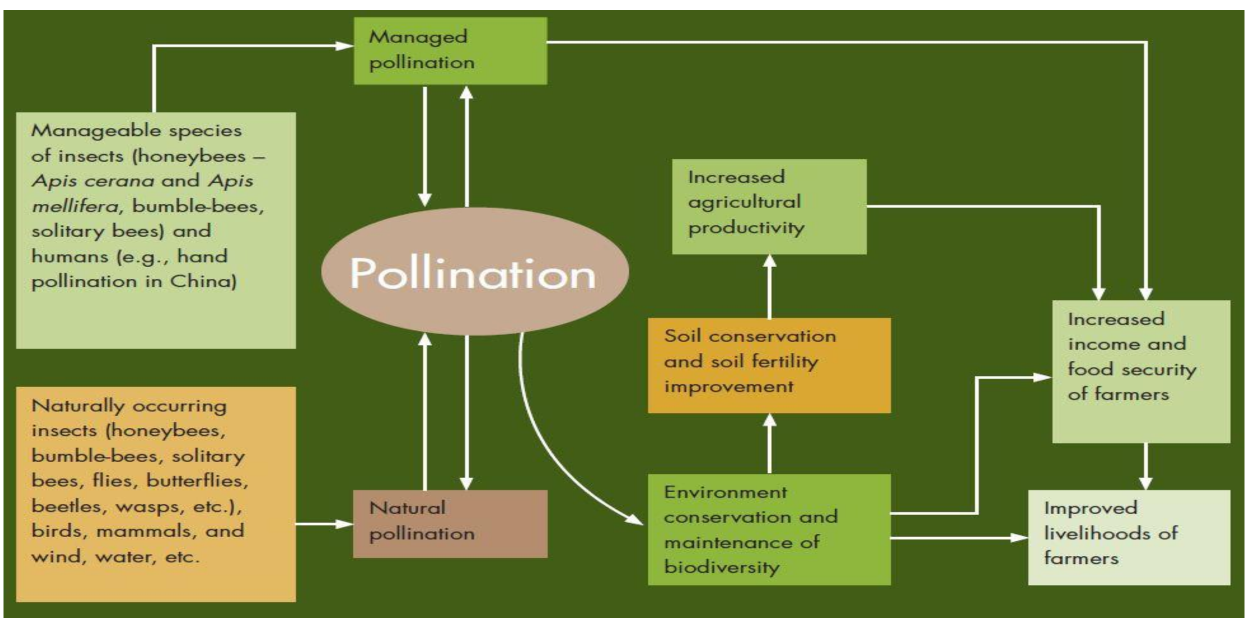
pollinators (Southwick & Southwick 1992). Klein et al. (2007) evaluated the extent of the reliance of agriculture on animal pollinators in 200 countries and found that about 70% of crops used globally as human food are dependent on animal pollinators. Looking at all crops traded on the world market except self-pollinated, wind-pollinated, or parthenocarpic crops, they found that pollinators are necessary for 13 crops and that production is highly pollinator dependent for 30 crops, moderately for 27, slightly for 21, unimportant for 7, and of unknown significance for the remaining 9 crops. McGregor (1976) reported that perhaps 33% of our total diet is dependent, directly or indirectly, upon insect pollinated crops. Among insects, different species of bees including honeybees, bumble-bees, stingless bees, and solitary bees are the most effective pollinators of crops. Over 25,000 species of bees are reported to pollinate over 70% of the world's cultivated crops. About 15% of the world's 100 principal crops are pollinated by manageable species of honeybees, bumble-bees, and solitary bees, while at least 80% are pollinated by other naturally occurring insect pollinators (Nabhan & Buchmann 1997).

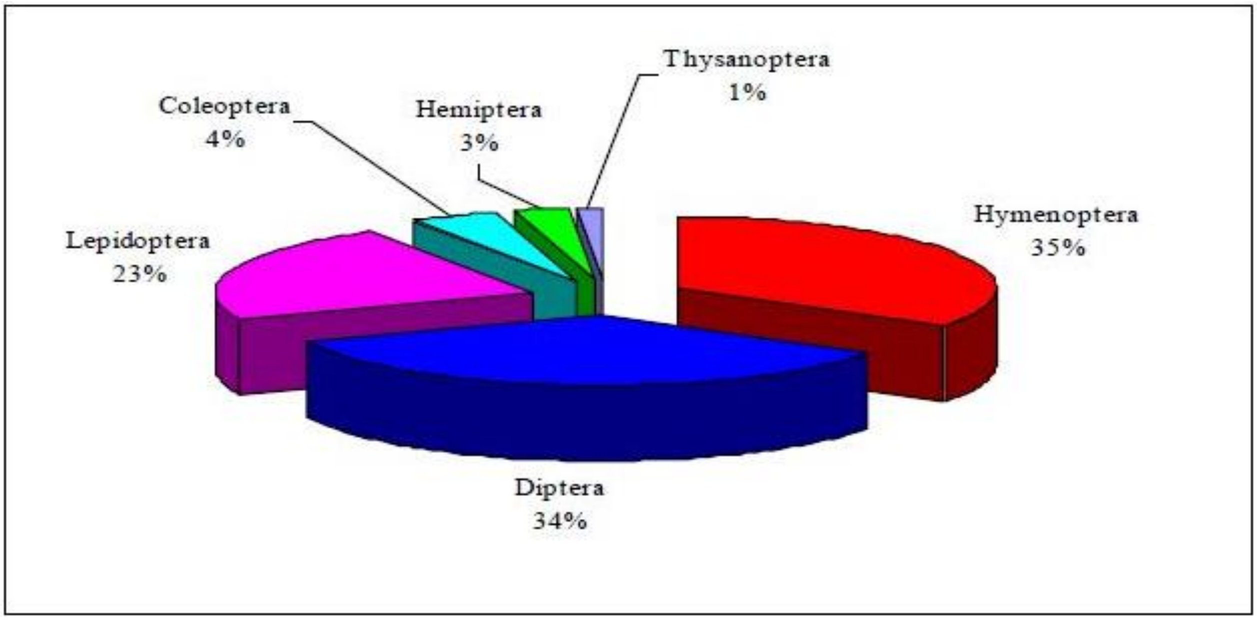
All the cross-pollination arid and semi-arid horticultural crops require pollinizers (pollen source) to ensure commercial quality fruit and yields. For satisfactory cross-pollination pollinizers and main variety bloom periods must overlap and the pollinizer variety must have viable pollen. The pollinizer variety must be located near the producing tree. Bees and other insect's pollinator must be present in the orchard and should be active during flowering. Attractive weed flora, such as mustard and wild radish, should not be present as they attract bees away from horticultural crops. The pollinizer cultivar should be planted in adequate ratio. Artificial or hand pollination also practiced in arid horticultural crops such as date palm and custard apple for high yield, uniform and better fruit size.

Figure 1. Role of pollination in improvement of agricultural productivity and rural livelihoods



Source: Partap 2011

Figure 2. Different insect pollinator species on temperate fruit crops in Himachal Himalaya



Source: Raj & Mattu 2014

A good pollinated flower has contained high seeds, with an enhanced capacity to germinate and leading to bigger and better shaped fruit. Quality pollination can also reduce the time between flowering and fruit setting and provide protection from the risk of exposing fruit to pests, disease and agrochemicals. The important horticultural crops of arid and semi-arid regions includes as ber (*Ziziphus mauritiana*), aonla (*Emblica officinalis*), date palm (*Phoenix dactylifera*), pomegranate (*Punica granatum*), kinnow (hybrid of Citrus nobilis x Citrus deliciosa), bael (*Aegle marmelos*), custard apple (*Annona squamosa*), fig (*Ficus carica*), Phalsa (*Grewia asiatica*) jamun (*Syzygium cumini*), and in vegetables such as cucurbits, legumes, khejri (*Prosopis cineraria*), and solanaceous crops, spices, medicinal and aromatic plants. In these arid horticultural crops various floral biological activities such as pollination, fruit set, retention, quality (size, shape, color etc.), shelf life, harvesting period are directly or in-directly influenced by pollinators, pollinizers and environmental interaction which determine their bearing capacity and yield efficiency. Plants with higher level of pollination and fertilization produce more seeds with larger fruit size and improperly pollinated plants produce less number of seeds with misshaped fruit owing to uneven growth in ovarian tissues. The role of various insect pollinators in important arid and semi-arid fruit, vegetable and spices crops are mentioned below.

Ber (*Zizyphus mauritiana* Lamk.)

In ber (*Z. mauritiana*) flowering starts during September and last up to November. The flowers are bisexual and reveal protandry (dichogamy). Anthesis occurs during noon and the floral span is 16.30 hr. The species exhibits a definite female bias in its numerical sex ratios. Flowers are simple, small, and greenish-cream in colour and give aminoid smell during hot and dry days. The nectar quantity seems to be very less but swollen floral disc deceitfully created impression of nectar drop, which shines in the light, creating sufficient stimulus to attract a number of insect species (Mishra et al. 2004, Haldhar et al. 2016; Haldhar et al. 2018). The flowers are axillary cymose in short clusters with exposed nectar on floral disc. Flowers possess adaptations to the sensory abilities, mobility, and morphology of pollinators for ensured pollination (Faegri & Van der Pijl 1979; Samadia & Haldhar 2017). Flowers of different species often are having special characteristics (syndrome) to attract particular guild of pollinators. For instance, flowers visited by insects are, in general, small, scented and contain small amount of nectar. Ornithophilous flowers of plants are usually large, orange or yellow and contain large amount of dilute color with unscented nectar (Faegri & Van der Pijl 1979). The flowers of *Z. mauritiana* are primarily adapted for insect's pollination in field condition. The characteristics of flower of ber species are frequently associated with entomophilous syndrome. Kumar (1990) reported that the insect visitors, *Apis* spp. was observed foraging on ber plant for nectar and pollen while dipteran and lepidopteran insects are foraged only for nectar. Singh (1984) reported that honeybees and other hymenopteran insects on ber were more active on upper branches while housefly and other dipteran insects were abundant on middle and lower branches. Substantial insect activity is found in the ber plantation during flowering owing to the nectariferous disc. Therefore, insects appear to be the important pollinating agents. Honey bees (*Apis* sp.), house flies (*Musca domestica*) were reported to play an important role (Teaotia and Chauhan, 1964). In addition, yellow wasp (*Polistes herbraeus*) also found an important pollinator (Dhaliwal, 1975). Maximum insect activity during the day is between 11 A.M. and 3 P.M. Although Ackerman (1961) observed highest numbers of honey bees, houseflies and lady beetles (*Coccinella novemnotata*) in jujube flowers in Chico.

A total of 86 species of insects were recorded during the blossom of *Z. mauritiana* for seven days period. This insect community consisted of 30 species of flies, 32 wasps, 18 butterflies and 6 bees. Thus wasps contributed maximum (37.20%) to the pollinator association followed by flies (34.88%), butterflies (20.93%) and bees (6.97). The flowers of this plant are mainly visited by flies and wasps. The relative abundance of different insect's species varied among four pollinator types (Mishra et al. 2004). Yadav (1990) has reported that flies and wasps are the chief pollinators of ber plant. House (1989) and Jones and Crome (1990) are of the opinion that visitation and pollination by flies, often in combination with pollination by Hymenopteran insects, forms a dominating trait amongst entomophilous plants. Mishra et al. (2004) reported that many species of wasps like, *Cerceris tristis*, *C. albopicta*, *C. pictiventris*, *C. pulchra*, *C. suphureus*, *Tachytes erythopoda*, *Oxybellus squamosus*, *Rhynchium molleryii*, *Sceliphron* *madraspatanum*, and *Ammophila nigripes* were numerically abundant in ber field. The flies species like, *Syritta pipiens*, *Antherogona nudiseta*, *Musca conducens*, *Daucus cucurbitae*, *Antherogona oreintalis*, *Musca sorbens*, *Physiphora aenaea*, *Ischiodon scutellaris*, *Myospila lenticeps* and *Paragus serratus* were abundant in the ber field. The butterflies like *Zizera gaika*, *Tarucus theophrastus*, *Tarias hecabe*, *Precis almana*, *P. brassiceae*, *Spindasis natalensis*, *Euploea coreta* and *Atelta phalantha* were recorded comparatively higher values for relative abundance. The abundant bees were *Crocisa ramosa*, *Halictus sp.*, *Apis florea* and *Apis indica*. The establishment of precise activity thresholds is difficult and depends upon a combination of factors include not only weather variables, but also physiological and behavioral state of insects, in addition to floral resource availability (Stone 1994; Haldhar et al. 2013; Karuppaiah et al. 2015). Temperature has considerable effect on pollinator systems that affecting the activity of insects or by altering the volatilization of attractants and nectar flow (Williams & Williams 1983). This study implies that insect activity initiation is limited by temperature, and activity termination is determined either by a decline in light intensity or possibly, by a decline in pollen-nectar availability (Vicens & Bosch 2000). Standing crops of pollen and nectar may condition daily activity rhythms, and mask the effect of weather factors, especially in endothermic species (Stone et al. 1998). Due to the occurrence of cross pollination along with self and cross incompatibility and pollen sterility, fruit-set in the ber mainly depends on timely pollination and its related factors like pollinators and environmental interaction and on the success in fertilization. In ber both self and cross incompatibility has been reported (Pareek, 1983). Cultivars 'Banarasi Pewandi', 'Thornless' and 'Banarasi Karaka' were self-incompatible whereas the later two were reciprocally cross-incompatible (Teaotia and Chauhan, 1964). No fruit set occurred in 'Gola', 'Seb', 'Jogia', 'Aliganj', 'Ponda' and 'Ilaichi' when the flowers were covered with butter paper bags. Seb is an early variety and acts as a good pollinizer for a number of varieties.

Pomegranate (*Punica granatum* L.)

Pomegranate is both self- and cross-pollinated by insects, mainly bees. Wind pollination (anemophily) is reported to occur, but infrequently (Morton 1987). Self-pollination of bagged flowers has resulted in 45% fruit set. Cross-pollination has increased yield to 68%. In hermaphrodite flowers, 6 to 20% of the pollen may be infertile while in male, 14 to 28%. The size and fertility of the pollen vary with the cultivar and season. The percentage of fruit set observed by hand pollination and pollination under natural conditions (Nath & Randhawa 1959a; Josan et al. 1979; Morton 1987). Nalawadi et al. (1973) indicated that pomegranate is a cross pollinated crop. According to Singh et al. (1978), pomegranate is often cross-pollinated crop whereas Pross (1938), working with four pomegranate cultivars in central Asia, considered it to be a self-pollinated crop. The percentage of fruit set was high in Japanese Dwarf, Dholka and Muscat White, 26.9, 20.8 and 25.5%, respectively and low in varieties

(Kandhari 7.3%, 'G.B.-I' 5.4% and Patiala 4.7%). In Dholka and Muscat White, the percentage of seed production was high, 37.4 and 42.9% in comparison to other varieties where values ranged from 25.5 to 29.1 % (Nath & Randhawa 1959 a & b). Emasculation and bagging studies on Indian, Turkmen, Israeli, and Tunisian pomegranate cultivars indicate that pomegranate flowers can self-pollinate and produce normal fruit (Mars 2000; Levin 2006). It was also observed that the degree of fruit set by self-pollination varies among different pomegranate cultivars (Kumar et al. 2004).

Bee pollination could improve the fruit set and weight of pomegranate fruit significantly compared with self-pollination (Derin & Eti 2001; Tao et al. 2010). With cross pollination, fruit set is increased by 68 per cent and with improvement in fruit quality (i.e. number of seeds per fruit, fruit size) additionally (Anonymous 2006). According to Nath & Randhawa (l959a & b), in Muscat White, 46% fruit set was obtained by bagging the flowers and effecting self pollination. Cross pollination, however, improved the fruit set to 67.9%. The concentration of pollen in the atmosphere was found to be quite low for wind pollination. Cross pollination was effected by three insects, namely *Camponotus* spp., *Apis* spp. and *Papilio demoleus*. There is little quantitative data available with regard to the efficiency of honey bees in the pollination of pomegranate; however, McGregor (1976) stated that pomegranate growers in California arrange for honey bee colonies around their fields for fruit production.

Aonla (*Emblica officinalis*)

Aonla is basically a cross pollinated plant. Wind, honeybees and gravity play an important role in effective pollination. The pollination studies showed considerable variation with respect to fruit set and retention. The use of pollinators (honey bees) and pollinizers in aonla orchards is necessary for increasing the fruit yield (Allemullah & Ram 1990). Planting of 10% pollinizer is suggested for better fruit setting. In aonla orchard NA-6 is suggested as best pollinizer for NA-7 cultivar and Chakiya for cultivars NA-7 and Banarasi.

Citrus (*Citrus* spp.)

Different citrus species differ in their pollination needs and even pollinators differ in their choice for different citrus species (Roubik 1995). Some sweet orange and citrus varieties are partially or completely self-incompatible which makes them dependent on insect pollinators for pollination (Sanford 1992). However, it is confusing for pollination in grapefruit with no insect pollination is required for fruit set (Roubik 1995) while others considered them the most important to increase fruit production. Depending on the variety and conditions at the site, honeybee pollination may increase fruit set, fruit size and seed number. Although cross pollination is required, use of honey bees remains the most consistent, effective and economical means of ensuring adequate yields. Mehmood et al. (2015) reported that eight insect pollinator species *viz. Apis florea*, *Xylocopa* sp, *Pieris brassicae*, *Danaus plexippus*, *Papilio demoleus*, *Papilio hyale*, *Eumerus tuberculatus* and *Musca domestica* were observed visiting regularly on citrus (*Citrus* *limon*). Foraging activity of insect pollinators was maximum at 0800-0900 and minimum during 1700-1800 hours. Hymenopteran pollinators were higher in numbers (42%) followed by Lepidopterans (33%) and Dipterans (25%). *A. florea, E. tuberculatus*, and *P. demoleus* were consistent and frequent visitor on both fruit plants. Karmakar (2013) found frequent visits of *A. florea* and Diptera during 0900 hours and Lepidoptera during 1000-1130 hours on *Citrus aurantiifolia.* Majority of insect pollinators during morning times possibly owing to availability of abundant food resources (nectar) compared to noon and evening. In Kagzi Kalan lemon, 10% plant of pumello should be planted which serve the purpose of pollinizer to get high yield.

Phalsa (*Grewia asiatica*)

In phalsa, bearing of flowers start after 15 to 18 months of planting but the good yield is obtained only after three years of planting. The flowering starts in the month of February-March and continues for almost one month. The flowers are small and greenish yellow in colour. Although phalsa flower are hermaphrodite but cross pollination is essential for better fruit set. Gill et al. (2001) found that fruit set (61.60%) in open pollination was significantly higher than the self-pollination (23.00%). Irrespective of modes of pollination, there were non-significant differences on fruit set in tall (45.00%) and dwarf (38.01%) types of phalsa. The main insect pollinators for phalsa are *Apis florea*, *A. mellifera*, *A. dorsata*, *Megachile bicolor* and *Chalicodoma cephalotes* were observed foraging both nectar and pollen, while other foraged for nectar only. Dey et al. (2016) reported that the flowers generally open in the early morning (7:00 hrs 8:30 hrs). Different members of Hymenoptera, Lepidoptera, Diptera, Coleopter (beetles), mammals and birds *etc.* were found to visit for their forage. The 70% fruits formation were observed in natural open condition and 20% fruits formation were found in netted condition. But in bagged condition no fruits formation were observed in this plant. Free (1970) reported that *Apis dorsata*, *Apis cerena indica*, *Trigona* sp., *Ceratina* sp., *Amegilla* sp., *Megachile* sp., *Halictus* sp., *Xylocopa* sp., *Eumenes* sp, ants, members of Lepidoptera and Diptera, squirrel and bird *etc.* were found to visit flower for collecting their food materials. The large group of Hymenoptera comprises some of the most interesting, highly evolved, and economically most important pollinating insects. The role of bees has been recognized in pollination since early time.

Different insects (members of Hymenoptera, Lepdoptera and Diptera) were found to visit phalsa flowers for their forage which is quite similar with the observation of Parmar (1976) and Manzoor-ul-haq et al. (1979). Inspite of insects birds and squirrels are also found to visit flowers whether Parmar (1976); Manzoor-ul-haq et al. (1979) found only insect visitors in the taxa. Among the visitors *Apis dorsata*,*Trigona* sp. and *Megachile* sp. are the frequent visitors and pollinate the flowers while collecting nectar as well as pollen and can be considered the potential pollinators of phalsa flowers, whether according to Manzoor-ul-haq et al. (1979), *Apis florae* and several species of

Halictus (Halictidae) and *Andrena* (Andrenidae) were the most common visitors and according to Parmar (1976), African honey bees were the most abundant visitors of the species.

Table 1. List of flower visitors of *Grewia asiatica* L

Flower visitor	Visiting time	Forage matter
Hymenoptera		
Apis dorsata	Day	Pollen and nectar
Apis cerena indica	Day	Pollen and nectar
Trigona sp.	Day	Pollen and nectar
Amegilla sp.	Day	Pollen and nectar
Megachile sp.	Day	Pollen and nectar
Halictus sp	Day	Pollen and nectar
Eumenes sp	Day	Pollen and nectar
Xylocopa sp.	Day	Pollen and nectar
Camponotus compressus (Ant)	Day and night	Pollen and nectar
Lepidoptera	Day	Nectar
Butterflies	Day	Nectar
Borbo sp.		
Diptera	Day	Pollen and nectar
Musca sp.		
Mammals	Day	Pollen and nectar
Squirrel (Funambulus sp.*)*	Day	Pollen and nectar
Bird *(Nectarinia* sp.*)*		

Source: Dey et al. 2016

Fig (*Ficus* spp.)

The figs grown commercially are basically of three types *i.e.* the common type (Mission cv.) develops its fruit parthenocarpically, the Smyrna type (Calimyrna cv.) must be pollinated with pollen from the inedible caprifig. The San Pedro type produces its first crop of the season parthenocarpically, but its second crop develops only if its flowers are pollinated (Eisen 1897; Condit 1938). The Kadota cv. is a common type that will produce fruit parthenocarpically, but if pollinated its seeds will develop, a feature that is desired if the figs are to be dried, but undesired for preserved (Condit 1927). Smyrna and second crop San Pedro figs are pollinated exclusively by the hymenopterous fig wasp (*Blastophaga psenes* (L.), which overwinters in the caprifig fruit. The use of this wasp is the oldest form of man-manipulated insect pollination, a system referred to as caprification. With the exception of date pollination, this is the oldest form of controlled pollination in plants (Condit & Enderud 1956). According to Betts (1940) these insects play important role in fertilizing the fig was known in 1782, just 11 years before noted his pollination by insect. This relationship was later challenged and proved a myth by the Italian government (Reasoner 1891). In 1887, when the astute Gustav Eisen announced in Fresno, Calif., the necessity of

importing these wasps, he was hooted down and some of the mob whistled (Condit and Swingle 1947), but the need for these insects is now an acknowledged fact.

Date palm (*Phoenix dactylifera*)

In date palm, for fruit production pollen must be transferred from staminate trees to pistillate ones. Leding (1928) showed that delay in placement of pollen on pistillate flowers reduced production to 89 % by the second day, to 70 % by the fourth day, to 54 % by the sixth day, to 46 % by the eighth day, and to 23 % by the eleventh day. Nixon (1928) observed that the source of pollen affected the date of ripening (10 days) and seed shape and size. Later, he showed that pollen not only affects the seed but also the fruit pulp, which he termed “metaxenia”. Nixon (1959) stated that pollination of 50 to 80 % of the pistillate flowers is sufficient for a full crop. If sufficient staminate or "male" trees are near the pistillate or "female" ones, wind and sometimes insects transfer sufficient pollen for adequate fruit set. However, the grower grows pollinizer variety (male trees) to a minimum as they yield no fruit and distributes the pollen manually. It is the oldest (before 800 B.C.) known means of controlled pollination of crops by hand pollination. Date palm is dioecious with female and male flowers occurring on separate plants. Artificial pollination is crucial for economical crop. Pollen grains from different male palms affect yield and fruit quality in date palm and this phenomenon known as “Metexenia” (Swingle, 1928). Higher fruit set resulted from pollen of some males than others owing to compatibility of male and female varieties. Shaheen (1986) reported that pollination is considered the most important factor affecting fruit set yield and quality in date palm. Pollen can change some fruit morphological properties and fruit texture which effect on the endosperm (embryo and albumen). It affects fruit size, shape, weight and time of ripening (Rahnama & Rahkhodaei 2014; Haldhar et al. 2015; Haldhar et al. 2017). In fact, Pollen has Xenia and Metaxenia affect to broad efficacy on chemical, quality and quantity characteristics fruit. Therefore, proper selection of pollinizer for pollination is important because this specification affects size of fruit, development rate and time of fruit ripening (Hussein et al. 1979; Swingle 1928). Awad (2007) evaluated different types of pollen (Ahmar, Akhzar, Fard, Khnizy, Maghool and Shekar) on Nabat Sayf female variety and reported that pollen could affect fruit set properties. Higazy et al. (1982) used four different pollen on five date cultivars and found significant differences among fruit weight and fruit pulp to seed ratio but no difference among pollen. Hussein et al. (1979) observed significant difference in fruit pulp quality but no difference in seed quality using four types of pollen to pollinate Nabat sayf in Saudi Arabia. Osman (1974) compared seven kinds of pollen grain on Degle Nour and reported that genetic potential has a main role in metaxenia property as same as growth regulators. Pollen grains from different male date palms influenced the size and shape, fruit set, yield and fruit physical and chemical characteristics. Mothew et al. (1975), El-Hammady et al. (1977), Shaheen et al. (1989a, b) and El-

Salhy et al. (2010) were reported that pollinizers (pollen sources) affected fruit and seed characteristics and exhibited metaxenic effect depending on female cultivar used.

Jamun (*Syzygium cumini*)

Jamun blooms from March to April. Natural pollen transfer in the species was efficient and fruit set following open-pollination was quite high. Despite synchronous nature of anther dehiscence and stigma receptivity, selfing in a flower was found to coexist in nature with cross-pollination due to pollinator efficiency and pollen grain size. Selfing was encouraged by geitonogamous mode and the species was suited to insect and wind pollination (Bajpai et al. 2012). A total of 33 species consisting of bees, wasps, flies, beetles, butterflies (diurnal foragers), the hawk moth (crepuscular forager), and the reptilian (nocturnal forager) was reported as pollinator in jamun. The bees included *Apis dorsata*, *A. cerana*, *A. florea*, *Amegilla* sp., *Stizus* sp. and *Trigona iridipennis*. Among them, *Trigona* bees foraged for nectar and pollen, while all others for nectar only. The wasps were nectar foragers and they were *Eumenes* sp., *Vespa cincta* and *V. orientalis*. Flies (*Chrysomya megacephala* and *Helophilus* sp.) were occasional nectar foragers and beetles (*Popillia impressipyga*) and one unidentified species; the previous was a resident forager feeding on flower parts. The butterflies including *Papilio polytes*, *Graphium nomius*, *Catopsilia pyranthe*, *C. pomona*, *Euploea core*, *Tirumala limniace*, *Precis iphita*, *Junonia lemonias*, *Melanitis leda*, *Danaus genutia*, *Neptis hylas*, *Mycalesis perseus*, *Moduza procris*, *Arhopala amantes*, *Pseudocoladenia indrani*, *Borbo cinnara*, *Hasora chromus* and *Celaenorrhinus ambareesa* were regular foragers of the jamun.. The sphingid, *Cephonodes hylas* was the only diurnal moth visiting on the flowers regularly. The African fat-tailed gecko, Hemitheconyx *caudicinctus* was a nocturnal resident for nectar on jamun. The first visitor to just open flowers in the evening is the diurnal hawk moth, *Cephonodes hylas*; it continued foraging from 1600–1900 hrs. Of the total foraging visits made by insects except beetles, bees constituted 25%, wasps 15%, flies 3%, butterflies 50% and hawk moth 7% (Raju et al. 2014). Williams & Adam (2010) obsereved that *Syzygium tierneyanum*, *S. sayeri*, *S. floribundum* and *S. cormiflorum*. *S. tierneyanum* are visited by 45 species of nectar feeding animals; honeyeaters and hawk moths are considered as most important pollinators due to their abundance and foraging behavior despite the honeybees being the prolific visitors. Blossom bats and honeyeaters contribute about 50 % of the pollination rate and the remaining contributed mainly by butterflies, flies, thrips and wasps in *S. sayeri*. The mass-flowering *S. floribundum* is pollinated by a guild of insects. In *S. cormiflorum*, birds, insects and particularly blossom bats are effective pollinators; this with hawk moths constitutes a greatest percentage of successful pollination (Williams & Adam 2010). *S. paniculatum* with generalized pollination strategy is visited by a variety of insects (Payne 1997). In Sulawesi, *S. syzygiodes* and occurring in the lowland rain forest is entomophilous and pollinated by a association of short-tongued unspecialized insects. In Samoa, *S. inophylloides* and *S. samarangense* are frequently foraged by birds (Cox et al. 1992). Bats are important pollinators of *Syzygium* species (Banack 1996). In East Java, *S. pycnanthum* is reported to be visited by a guild of insects by Mudiana & Ariyanti (2010). *S. mamillatum* is pollinated by generalist bird species in Mauritius (Kaiser et al. 2008). In southern India, *S. cuminii* with chiropterophilous pollination syndrome is in reality entomophilous and effected by 24 species of insects consisting of nocturnal, crepuscular and diurnal ones. It is also observed that entomophily is ineffective and as a result it has evolved certain floral traits that facilitate effective anemophily (Reddi & Rangaiah 1999–2000).

Bael (*Aegle marmelos* C.)

Bael is only about 5 % flowers are self-pollinated and 95 % animal pollinated. It is mostly pollinated fruit crop which has entomophilous flowers by various insect pollinators like honey bees (*Apis dorsata*, *A. mellifera*), hover flies, yellow wasp, carpenter bee, weevil, black ants, butterflies *etc*. (Haldhar et al. 2010; Singh et al. 2011). Bees are considered as the best pollinators among all pollinators. Butterflies are occasional pollinators, and do pollination of crops while feeding on nectar. Flies, hoverflies and wasps are effective pollinators because they visit flowers to feed upon nectar (or in some species pollen) for essential nutrients for egg maturation and extending their life-span (Free 1993). Satapathy & Chandra (2017) reported that hymenopterans were the major floral visitors comprising of six species from four families viz., Xylocopidae, Apidae, Vespidae and Formicidae, followed by dipterans (One species from one family) *viz*., Syrphidae, Lepidoptera (three species from two families) viz., Pieridae and Arctiidae. The abundance of *Apis dorsata* was highest (7.90 bees/spike/5 minutes) followed by syrphid flies, *Eupeodes corolae* (3.45 visitors/spike/5 minutes) and *Apis mellifera* (1.20 bees/spike/5 minutes). Based on pollination index (Number of loose pollen grains sticking on the body of visitors × abundance), *A. dorsata* was found to be the most efficient pollinator of bael flowers followed by *Eupeodes corolae* and *A. mellifera* under Faizabad (India) conditions.

Table 2. Abundance of major insect pollinators on blossoms of *Aegle marmelos* C.

Species	Number of pollinators/spike/5 minutes during different day hours				
	6 am-9 am	9 am-12 noon	12 noon-3 pm	3 pm-6 pm	Mean
Apis dorsata	8.00 (2.92)	12.60 (3.62)	4.40 (2.21)	6.60 (2.66)	7.90 (2.85)
Apis mellifera	2.40 (1.70)	0.60 (1.05)	1.40 (1.38)	0.40 (0.95)	1.20 (1.27)
Eupeodes corolae	5.40 (2.43)	3.80 (2.07)	1.20 (1.30)	3.40 (1.97)	3.45 (1.95)

Figures in parentheses are the transferred (square root) means
Source: Satapathy & Chandra (2017)

Khejri (*Prosopis cineraria*)

The flowers of *khejri* are small, massed into globose heads and function as units of reproduction. The plant is self-incompatible and exhibits synchronous flowering to facilitate cross-pollination. It produces small quantities of sticky nectar, and has abundant pollen resources available for bee pollinators. Flowera are in the form of axillary spikes with the length of 7-11 cm, either solitary or in terminal panicles. Flowers posse yellow corolla, attracting large number of insects including large number of *Apis florea* and numerous other wild bees in the month of December and April. The flowers are also valuable for honey production. Fifteen species of bee were recorded visiting on trees in bloom. Maximum number of visitors of bee in *Trigona iridipennis*, followed by *Apis florea* and minimum time visitor bees are *Nomia elliotii* and followed by *Halictus lucidipennis* and *Nomioides comberi* (Haldhar 2012; Gorain et al. 2012). Honeybees were more common visitors to trees close to water, although bees may in fact fly considerable distances to obtain water (for example, honeybee species have been recorded foraging 10–20 km from their nest). In contrast, other bees, wasps and flies were actually more common visitors to trees far from water, and the total number of insect visitors was higher for trees away from surface water compared with those near water (Dyer & Seeley 1991; Beekman & Ratnieks 2000).

Table 3. Bee species reported in *Prosopis cineraria* in arid and semi arid region of Rajasthan

S. No.	Order	Family	Genus & Species	No. of bees
1.	Hymenoptera	Apidae	*Apis dorsata* Fabricius	08
2.	Hymenoptera	Apidae	*Apis florea* Fabricius	16
3.	Hymenoptera	Megachilidae	*Icteranthidium sinapinum* Cockerell	12
4.	Hymenoptera	Megachilidae	*Eoanthidium punjabensis* Gupta & Sharma	08
5.	Hymenoptera	Halictidae	*Halictus constrictus* Smith	06
6.	Hymenoptera	Halictidae	*Halictus lucidipennis* Smith	05
7.	Hymenoptera	Halictidae	*Halictus torridus* Smith	07
8.	Hymenoptera	Megachilidae	*Megachile gathela* Cameron	08
9.	Hymenoptera	Megachilidae	*Megachile suavida* Cameron	06
10.	Hymenoptera	Halictidae	*Nomia elliotii* Smith	04
11.	Hymenoptera	Halictidae	*Nomia oxybeloides* Smith	08
12.	Hymenoptera	Halictidae	*Nomioides comberi* Cameron	05
13.	Hymenoptera	Halictidae	*Nomoides sp.1*	13
14.	Hymenoptera	Halictidae	*Nomoides sp.2*	12
15.	Hymenoptera	Apidae	*Trigona iridipennis* Smith	25

Source: Gorain et al. 2012.

Fields beans

An average field bean plant produces 50-80 flowers, but a large proportion of flowers are shed during the season. Flowers of field bean are borne on a straight upright stalk, often a foot high on which they open in succession. The sepals are jointed into a single five-toothed calyx. The irregular white corolla, with black or brown spots, consists of a standard petal, two wing petals, and two lower petals, united along their outer edges to form a keel. The style bears a brush of long hairs just below the stigma; in the tripping process these hairs brush the pollen out of the keel onto the bees that visit to take nectar (Kambal et al. 1976). The legume family is a major source of forage for bees and is principally bee-pollinated. Legumes and bees have been intimately associated with one another throughout their evolutionary histories (Kalin-Arroyo 1981). Field bean flowers attract almost exclusively Hymenoptera, particularly apoid bees having sufficient strength and weight to lower the hull and wing petals, to disclose the stamens and pistil for foraging for pollen and / or nectar. Aouar-sadli et al. (2008) reported that the most abundant species on broad bean flowers was the solitary bee *Eucera pulveracea* which alone accounted for 49.9% of observed visits. The visits of this species were both very frequent and very effective that could be fertilizing in all cases. They also observed the honey bee *A. mellifera* visiting the flowers actively, but seemed less adapted to the floral morphology of *Vicia faba* compared to *E. pulveracea*. Ten species of bees are foraging on broad bean flowers belonging to 3 families *viz*; Apidae, Anthophoridae and Halictidae. The most abundant species on the broad bean flowers was *Eucera pulveracea*, which alone contributed for 49.9 % of the total population, where as honey bees accounted for 42 % of total Apoidea visitors to broad bean. Baddiyavar (2013) reported that the 35 species of insects belonging to Hymenoptera (89%), Lepidoptera (5%) and Diptera (6%) visited field bean flowers. The major species included *X. latipes*, *X. amthystina* and an unidentified species of *Xylocopa*, *Ceratina binghami*, *Trigona* sp was the most frequent visitor, constituting more than 50 per cent of all visits to the flowers, followed by *Ceratina binghami* (38.28%). The number of visits of insects was significantly higher as compared to other flower visitors like *Amegilla zonata* (11.71%), *Trigona* sp. (7.03%), and a eumenid wasp, *Odynerus* sp. (7.81%). A forager spent on an average 3.9±0.74 sec per flower during post monsoon season and 4.1±.07 in summer season. Field bean plants that were left for open pollination set significantly higher number of pods (66.06 and 61.02% in the first and second seasons, respectively) as against caged plants which were prevented flower visitors (34.48 and 31.80%).

Cucurbits

The cucurbits flowers are visited by a number of insect pollinators. Cucurbit flowers encourage bee visitation for several reasons. All cucurbit flowers have the entire anthesis period (or at least a portion) during daylight hours, which favor visits by diurnal insects, and only a few cucurbits have flowers that open during night time. The calabash gourd is a cucurbit that receives visits from nocturnal insects. Various species of bees, wasps, ants, butterflies, flies, and beetles have been reported to provide pollination services to cucurbit flowers (Delaplane & Mayer 2000; Haldhar et al. 2018). Although its flowers start to open during evening hours, this cucurbit also receives visits from diurnal insects since the flower anthesis period lasts until the afternoon of the following day. At night, calabash gourd flowers receive visits from *Cyrtopeltis tenuis* bug for pollination services, and during daytime, bees are the primary insects responsible for calabash gourd flower pollination (Free 1993). Although there are more than 20,000 described bee species around the world, only a few are commercially managed as pollinators of cultivated plants (Cruz & Campos 2009). Again, the primary managed bee species utilized in commercial cucurbit production are honey bees and bumble bees. Honey bees are utilized mostly in open-field cucurbit culture, while bumble bees are used in protected culture more than in open-field conditions (Guerra-Sanz 2008). Honey bees are the most utilized manageable pollinators in commercial cucurbit crops around the world, since natural populations have spread throughout the world. The results regarding mean population of pollinators showed the highest population of honey bees (1.21/plot) among all pollinators and varieties while population of carpenter bees was lowest (0.03/plot). Population density of pollinators was observed highest during morning and evening times. Uncovered plots yielded significantly higher produce than covered plots. Cucumber crop requires insect pollination as an additional input for enhancing the yield (Shah et al. 2015). Nicodemo et al. (2009) stated that large and monoecious flowers of cucurbits produce plenty of nectar and pollen and attract a wide range of insect visitors, particularly honey bees. The population of carpenter bees has been recorded to be the lowest among the three pollinators. Although carpenter bees have been recorded as efficient pollinators of many crops but we could not found their abundance as compared to honey bees and butterflies. This may be because of absence of their colonies and climatic conditions. The population of pollinators tended to increase from the start of flowering and reached to its peak during the mid of season i.e. week 7 because of the flowering period of crop was on peak at this stage and then started to decrease due to maturity of crop and finished season of flowering. Honey bees population was recorded the highest population among all the pollinators.

Kieth (1995) assured that over 50% of pollination is affected by hymenopteran insects, while 20%, 15% and 10% of pollination is done by dipterans, beetles and lepidopteran insects, correspondingly, while the remaining 5% is done by insects belonging to other insect orders. The use of stingless bees (*Meliponine*) as pollinators of agricultural crops has been quite promising in some tropical regions. Studies have indicated success in both rearing and use of certain stingless bee species (e.g., *Melipona subnitida*, *Melipona quadrifasciata*, *Nannotrigona testaceicornis*, *Scaptotrigona* sp., and *Tetragonisca angustula*) for pollination of agricultural crops, both in open-field (e.g., guava) and protected environment conditions (e.g., eggplant, melon, watermelon, strawberry, pepper, tomato, cucumber); though, the utilization and application of stingless bees for commercial pollination purposes is still in the development phase (Bomfim et al. 2013; Bezerra 2014). These bees are unable to sting, have perennial colonies that can grow to high populations, and depending on the species, have the potential for rearing high populations in colonies; these characteristics suggest that stingless bees may have potential as pollinators in protected environment culture (Venturieri et al. 2012). The honeybee, *A. mellifera*, could be an efficient pollinating agent for commercial crops of *C. sativus* and *C. melo*. Fruits deriving from flowers which had been pollinated by honeybees had a better quality than those deriving from flowers without bee pollination in *C. sativus* (Couto & Calmona 1993) from manually pollinated flowers of *C. melo* (Marchini et al. 2006). However, *A. mellifera* usually visit cucumber flowers only when no other, more attractive flowers are present.

Seed spices

The most of the seed spice crops such as coriander, ajwain, nigella, fennel, cumin, dill and anise are cross pollinated in nature. Ramanujam et al. (1964) reported 55.86% natural cross pollination in coriander, 70.05 to 77.83 % in ajwain and 82.20 to 91.4 % in fennel. A number of insect visitors have been reported to visit the floral component of seed spices under natural field conditions. Twenty five insect pollinators (*Apis dorsata* F., *A. florea* F., *A. mellifera* L., *Ceratina sexmaculata* Smith, *Polistes hebraeus* and unidentified hymenoptera sp. 1(Hymenoptera); *Episyrphus balteatus*, *Eristalis* sp., *Musca domestica*, *Musca* sp. 1, *Musca* sp. 2, *Musca* sp. 3 (Diptera); *Dysdercus koenighii* F., *Oxycarenus leatus* Kirby., *Bagra dahilaris* Burmeister (Hemiptera); *Coccinella septempunctata* L., *Menochilus sexmaculatus* F. , Yellow beetle- unidentified (Coleoptera); *Chrysoperla zastrowi sillemi L*. (Neuroptera); *Plutella xylostella* L., *Lampiedis boeticus* L., *Pieris brassicae* L., and *Hellula undalis* Fabr. (Lepidoptera) are visiting the coriander crop. Amongst them, honeybees like *Apis mellifera*, *A. dorsata* and *A. florea* were the most prominent pollinators of this crop during entire flowering period (Meena et al., 2015). Coriander flowers produce a sufficient amount of nectar and pollen, and are visited by the range of insects. Honey bees are the primary pollinators and bee pollination can increase the yield by 122.2% over without bee pollination (Chaudhary & Singh 2007) and 187.3% higher using bee-Q. Honey bees are reported to play a vital role in enhancing the productivity level of different crops including most of seed spices crops (Sihag 1986). Similarly higher seed yield (96.55%) and germination (79.75%) of coriander due to insect pollination was recorded (Kumar and Jaiswal, 2012). Fennel is highly (80-90%) cross pollinated crop and *A. florea* is the most abundant pollinator comprising 81% of the total visitors. The crop is highly entomophilous with only 45-52% fruit set due to self-pollination (Shilova 1972). Honey bees (*Apis* cerana F., *A. florea* F. and *A. mellifera* L.) and syrphid *flies* are the most common pollinators (Chaudhary et al. 2002). Bee pollination abundantly increases the seed yield in fennel. The honey bees in cumin not only increased the production but also produce honey which is viscous, contain higher quantity of iron and unsaturated sugar with attractive aroma. In India, plants of cumin caged to exclude insects and plants not caged, yielded 209 and 501 seeds per plant, 0.92 and

1.82 g seeds per plant, and 1000 seeds weighed 7.2 and 8.8 g, respectively (Sihag 1986). In nigella, honeybees are the predominant pollinators and *A. mellifera* is a major pollinator among honey bees increased number of seeds set and yield produced in India. Many flies and bees act as pollinators of dill, play a considerable role in enhancement of yield. Irregular of yield is a common problem in seed set of nigella cultivated under semiarid conditions, the variations in crop production have been related to pollination failure (Wilcock & Neiland 2002). The main Nigella flower pollinators were honeybees (Ricciardelli & Persano, 1981) as well as bumble-bees (*Bombus lucorum*, *Bombus lapidarius*), wasps (*Polistes dominulus*, *Eumenes pedunculatus*, *Cerceris arenaria*, *Philanthus triangulum* and *Ammophila sabulosa*), *Halictus* sp., *Chrysis* sp. and *Lasioglossum* sp. are major flower visitors in Austria (Weber 1995).

Acknowledgments

The authors are thankful to Director, ICAR-Central Institute for Arid Horticulture, Bikaner, India, for providing facilities and advice required for experimentation, and to R. Swaminathan, Professor, Department of Entomology, MPUAT, Udaipur, India and Majeet Singh, Professor, SKRAU, Bikaner, India for critical discussion and suggestions.

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