Circular
Agricultural Systems

REVIEW

Open Access

https://doi.org/10.48130/cas-0024-0015
Circular Agricultural Systems **2024**, 4: e016

Bee pollination in vegetables: current status, challenges and prospects

Pratap A. Divekar*, Aradhana Mishra and Ravindr Kumar

ICAR-Indian Institute of Vegetable Research (IIVR), Varanasi, 221305, Uttar Pradesh, India
* Corresponding author, E-mail: pratapento@gmail.com

Abstract

Vegetables are very important for human health in the era of nutritional security because they are rich in vitamins, minerals, phytochemicals, and dietary fibers. Inadequate pollination due to the decline of pollinators is a major obstacle in achieving high productivity of vegetables that adversely affects the quality and quantity of seed production of vegetables. Bee pollination influences the profitability and productivity of several horticultural crops, especially vegetables. Bee pollination significantly increases crop quality and yield, and it also has widespread nutritional and monetary advantages. Bees encounter various obstacles that might negatively impact their quality of life, such as habitat destruction, effects of agrochemicals, insect-pest and diseases, and changing weather scenarios. The inadvertent usage of agrochemicals contaminates the vegetables and the bee products that are eventually consumed by humans. To meet the pollination demand of cross-pollinated vegetables like cucurbits and cole crops, 3−5 bee colonies/hectare are sufficient. Aspects like colony conditions, beehive densities, distribution, and time of placement of bee colonies must be considered to improve bee pollination. Bees are recognized as the most important pollinators because of their effectiveness and wider availability across the globe. To ensure food security, nutritional security, and to preserve biodiversity, bee pollination must be enhanced and given prime importance in vegetables. The integrated pollination technique, which recently arose but is in the infancy stage, links wild and managed bees on more bee-friendly farmlands to provide reliable and sufficient pollination.

Citation: Divekar PA, Mishra A, Kumar R. 2024. Bee pollination in vegetables: current status, challenges and prospects. *Circular Agricultural Systems* 4: e016 https://doi.org/10.48130/cas-0024-0015

Introduction

Vegetables are horticultural crops that are either annual or perennial and some of their parts (such as roots, stalks, flowers, fruits, leaves, etc.) can be eaten either cooked or raw[1]. The bioactive nutritional elements found in vegetables, such as dietary fiber, vitamins, minerals, and phytochemicals are crucial for human nutrition (phenolic compounds, flavonoids, bio-active peptides, etc.). These nutritional compounds lower the risk of chronic illnesses like obesity, diabetes, several tumors, and cardiovascular disorders[2,3]. The need for food security is rising as a consequence of issues including climate change, altering land uses, habitat destruction, and increasing human population. The modification of the subsistence system using commercial production of horticultural crops poses new challenges in the improvement of crop production and quality. The major constraint in the low productivity of vegetables is inadequate pollination due to the absence of pollinators, which leads to crop failures. The insufficient number of suitable pollinators causes a decline in the rate of fruit and seed productivity[4,5]. Fruits, nuts, oils, vegetables, and other crops can have higher yields and better quality when pollinated properly[6].

Insects contribute 80% of the pollination and of these, bees contribute 85% of the pollination and hence honeybees are referred to as the best pollinators[7]. Among plant pollinators, bees are the primary ones. The value of produce from agriculture used directly for human consumption was increased by EUR 153 billion, or 9.5%, primarily due to insect pollination[8]. Honey bees are regarded as reliable and effective pollinators of several vegetable crops, including radish, cauliflower, broad leaf mustard, onion, cucurbits, and cabbage. Because of their specificity, honey bees are the primary pollinators for cucurbits, which account for 84%–96% of all pollinators. One-third of the components of the average person's diet come from bee-pollinated plants; therefore, honeybees provide us with many benefits[9]. The significance of both pollinators and pollination activities in achieving sustainable agricultural production can be seen in terms of enhanced seed production. Most of the cross-pollinated vegetables (cucurbits and cole crops) are considered entomophilous, in which the pollination is, to a large extent, determined by the insects. The role of honey bees in enhancing the seed production of vegetables is well documented and the use of bee attractants can augment bee pollination[10−12] (Fig. 1).

Importance of pollination to cross-pollinated vegetables

Pollination, which is the initial stage in a plant's sexual reproduction, is simply the movement of pollen from the anthers to the stigma of a flower[13]. In exchange for visiting and delivering pollen, pollinating insects receive some sort of dietary benefit. Consequently, when pollinators and plants come together for mutual benefit, this process is called pollination. Pollination is necessary for unisex flowers that display a single-sex in the plants[14]. Pollinators increase the reproductive and genetic diversity of almost 80% of plant species[15]. There are several reasons for insufficient pollination, but the most significant one is a deficit in both the number and diversity of pollinators. Pollination with the help of honeybees is one of

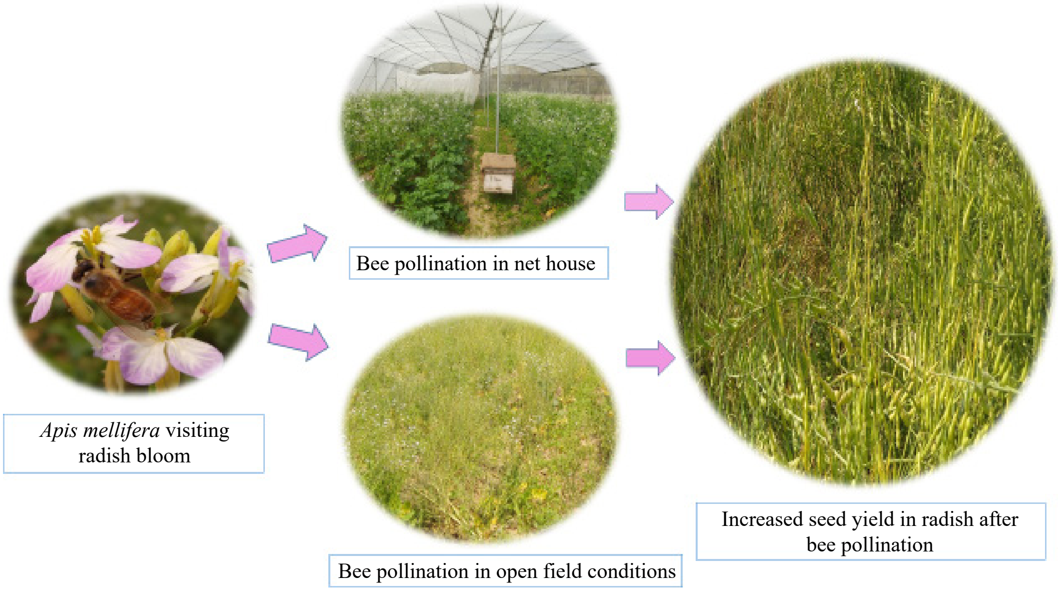

Fig. 1 Bee pollination in vegetables under controlled and open field conditions.

the economic and ecologically sustainable methods for increasing the yield of cross-pollinated vegetables[16,15]. The amount of pollen transferred to the female flower represents the quality of the pollination process; this is influenced by the activity of the pollinators and their movement between the flowers of the two lines[17].

Cole crops are cross-pollinated and can be grown in mild to cold climates, and most of them have perfect yellow flowers. In most of the cultivars, nectar secretion is achieved by two functional nectaries situated at the base of small anthers[18]. Thus, a large number of managed and wild pollinators are lured to the blooms for pollen and nectar and the flowers are thus pollinated. Cole crops are typically pollinated by honeybees, however quality as well as quantity of seeds will increase if wild pollinators are permitted to visit these crops[19−22].

Most cucurbits have imperfect flowers in which the reproductive structures, i.e., anthers and stigma, are not present on the same flowers, so these crops essentially need insects for pollination and fruit formation. There are hermaphrodite (male and female) flowers on the various plants of cucumber, melon, and squash. Thus, the fruit formation in these crops heavily relies on insect pollination. Thus, the absence of these pollinators leads to the loss of productivity of the cucurbit fruits by up to 95%[23]. A female/hermaphrodite flower's stigma with pollen grains indicates that bees have successfully pollinated the flowers. The primary source of pollination for the producers is wild pollinators, which is insufficient to meet the crops' pollination requirements[24]. In commercially grown cucurbits, insect pollinators are introduced to increase the pollinator density to obtain enhanced fruit production.

The pollinator-friendly management techniques, such as the preservation and/or restoration of nearby habitats for insect pollinators, a reduction in the use of harmful pesticides on bees and other measures to lessen the negative effects on pollinators should be adapted to maintain the high population densities of pollinators[25]. Additionally, it is crucial to learn about the floral biology of cross-pollinated vegetables to establish the appropriate management strategies for increasing fruit set and crop yield[24]. In vegetable crops like cauliflower, radish, cabbage, broad-leaf mustard, and lettuce the pollination by the honey bee enhanced the quality as well as the productivity of the seed[26,27]. Several findings supported the value of bee pollination and its contribution to enhancing crop yield (Fig. 1, Table 1).

Table 1. Percentage increase in yield of some crops due to bee pollination.

Sr No	Vegetable crop	Percent increase in yield
1	Cole	100.00–300.00
2	Radish	22.00–100.00
3	Carrot	9.00–135.00
4	Turnip	100.00–125.00
5	Cucumber and squashes	21.00–6,700
6	Onion	353.00–9,878
7	Cabbage	100–300.00

Adapted from Abrol[26].

Pollinators of vegetables

Several species of bees, wasps, ants, butterflies, flies, and beetles pollinating flowers of cucurbit and cole crops have been reported[28]. However, if an insect visits a flower without contacting the reproductive organs, it transfers pollen or carries non-viable pollen, or it visits the flowers when the stigma is not receptive, then it is not considered a pollinator[29]. Bees are the most explored pollinators for cucurbit and cole crops worldwide[20] (Table 2). They serve as pollinators for either open-field or controlled environments[28].

Bees have outstanding abilities as pollinators of cross-pollinated vegetables due to their behavioral and morphological adaptations such as:

(1) They are non-harmful to plants and their capacity to ingest pollen and nectar from the cucurbit and cole crop flowers enables them to touch the reproductive parts of plants.

(2) The branching hairs that cover their entire body surface increase the sticky pollen's adherence to their bodies and transference on the stigma of flowers that bear fruit[30].

Table 2. Primary bee visitors to flowers of some cross-pollinated vegetables.

Sr. No.	Crop	Bee floral visitors	Ref.
1	Cucumber (*Cucumis sativus*)	Honey bees (*A. mellifera*), *A. dorsata*, *A. florea*, bumble bees (*Bombus* spp.), *Melipona* spp., *Scaptotrigona* aff. depilis, *Melissodes* spp., *Pithitis smaragdula*, *Xylocopa fenestrata*	[12,15]
2	Calabash gourd (*Lagenaria siceraria*)	Honey bees (*A. mellifera*), *A. cerana*, bumble bees (*Bombus* spp.), *X. fenestrata*, *Xylocopa virginica*	[125]
3	Sponge gourd (*Luffa cylindrica*)	Honey bees (*A. mellifera*), *X. fenestrata*, *X. virginica*	[125]
4	Melon (*Cucumis melo*)	Honey bees (*A. mellifera*), *A. florea*, *A. cerana*, *Tetragonula iridipennis*, *Ceratina hieroglyphica*, *Ceratina binghami*	[126]
5	Pumpkin (*Cucurbita* spp.)	Honey bees (*A. mellifera*), *A. cerana*, *A. dorsata*, *A. florea*, bumble bees (*Bombus* spp.), *M. quadrifasciata*, *Trigona spinipes*, *Xylocopa* spp., *Agapostemon virescens*, *Augochlora pura*, *Dialictus* sp., *Halictus* sp.	[28]
6	Watermelon (*Citrullus lanatus*)	Honey bees (*A. mellifera*), *A. cerana*, *A. florea*, bumble bees (*Bombus* spp.), *Melipona* spp., *Scaptotrigona* sp., *Trigona iridipennis*, *Ceratina* spp., *Dialictus* spp.	[38]
7	Brocolli (*Brassica oleracea* var. *italica*)	Honey bees (*A. mellifera*, *A. cerana*, *A. Florea*), bumble bees (*Bombus haemorrhoidalis*)	[127]
8	Cabbage (*Brassica oleracea* var. *capitata*) and cauliflower (*Brassica oleracea* var. *botrytis*)	*A. cerana*	[27]
9	Radish (*Raphanus sativus*)	*Apis florea*, *Apis dorsata*, *Tetragonula iridipennis*, *Apis cerana*, *Lassioglossum* sp.	[128]

(3) Additionally, they have specialized foraging tactics and patterns, which enhances the probability of pollen grains adhering to the stigma[31].

Cucurbit flowers attract bees for several reasons. Only a few cucurbits have blooms that open at night and most of the cucurbit flowers, with few exceptions, spend all of their anthesis stages during the day, which encourages visits from diurnal insects[14]. The most often used insect pollinators of cucurbit crops are honey bees (*Apis mellifera*) and bumble bees (*Bombus* spp.), despite the fact that a variety of social and solitary bee species have been seen to visit cucurbit blooms frequently and provide pollination services[32]. Managed honeybees are the most common pollinator worldwide[33]. They feed on a plethora of angiosperms, have big colonies with plenty of workers, have been managed for a long time and are very inexpensive for producers to rent, making them ideally suited for agricultural pollination[34]. Despite increasing obstacles to this industry, beekeepers—from the amateur hobbyist to the expert commercial operator—provide millions of colonies to help agricultural pollination[35].

The squash bee (*Peponapis pruinosa*) is a solitary bee that is widely recognized for pollinating cucurbits particularly pumpkin and squash (*Cucurbita* spp.). The squash bee mainly visits the flower early in the morning when maximum flowers are open which is the ideal time for pollination[28]. The female bees, as compared to the males, are more effective, even though male bees are equally useful because they search for females inside the cucurbit blossom and enjoy the nectar[36]. The best pollinator for large-scale cucurbit production is the squash bee, which is less abundant in nature. There have been some reports of wild squash bee populations as good pollinators for the commercial cultivation of cucurbit crops like pumpkin and squash[37].

The stingless and solitary bees also play a role in pollination depending upon the area in which they are adapted. The proximity of adequate natural habitats to cucurbit crop fields during flowering presumably increases the abundance of these unmanaged bees[38]. In some tropical areas, the utilization of stingless bees (meliponines) to pollinate crops has shown to be highly effective. Some stingless bee species, such as *Melipona subnitida*, *Melipona quadrifasciata*, *Nannotrigona testaceicornis*, *Scaptotrigona* spp., and *Tetragonisca angustula* can be managed and used for pollination of horticultural crops both in open fields (e.g. guava) and protected environments (e.g. pepper, tomato, eggplant, and cucumber). But stingless bees nonetheless remain in the investigative and development stage when it comes to commercial pollination[39]. The potential use of stingless bees as pollinators in protected areas is effective since they cannot sting, have perennial colonies that can increase in number and depending on the species, maybe able to rear large populations in colonies[31].

The structural and physiological adaptations of stingless bees make them suitable pollinators as they have modified structures for the collection of pollen and nectar and no stinging behavior makes them easier to handle[40], especially in net-houses/greenhouses. Some stingless bees in the genus *Melipona*, exhibit vibrational behavior to collect pollen from plants containing poricidal anthers like tomato[40]. *Melipona quadrifasciata*, a neotropical stingless bee, is used for pollination in tomatoes grown in greenhouses because it produces more fruit with less mechanical damage[41]. Additionally, stingless bees play a significant role in pollinating greenhouse cucumber crops, increasing fruit weight and production[42]. The stingless bee *Heterotrigona itama* and hand cross-pollination increased crop yield and fruit quality, allowing cucumbers to grow bigger, longer, and heavier fruits[43]. Similar to this, manual cross-pollination and stingless bee pollination of rock-melon (*Cucumis melo* var. *reticulatus*) exhibited an advantage over self-pollination in terms of fruit set and the quantity of seeds per fruit[44].

The carpenter bee, *Xylocopa pubescens*, has been reported to pollinate honeydew melons (*Cucumis melo Inodorus* group) grown in greenhouses. While this species visited flowers for shorter periods than the honey bee, it was shown that both bees' pollination produced a comparable amount of fruit and seeds, and *X. pubescens* fertilization tripled the amount of fruit set compared to honey bee pollination[45].

Aspects of bee colony management to be considered for bee pollination in vegetables

The number of bee colonies in the field per unit area influences the pollination quality. The density of bee colonies per unit area, colony strength, location and time of placement of bee colonies as well as weather conditions affect the pollination process. Strong bee colonies with a lot of uncapped brood and disease-free workers lead to better outcomes when the crop is at 5%–10% blossoming stage. The following aspects should be carefully taken into consideration to enhance bee pollination efficiency.

Colony conditions

In general, the percentage of the population that forages will increase as the size of the honey bee colony expands. The proportion of forager bees in smaller colonies is therefore lower. Higher numbers of bees as well as a greater percentage of the population acting as foragers, who are in charge of pollination, are produced by larger colonies[46]. Forager activity must also be closely observed in the morning to see whether the foragers are searching the target vegetable crop for floral resources[47]. Colonies that are used for pollination should be resilient, have a high brood population and the queen should be under two years old[13].

There should therefore be a minimum of six frames in the bee hives, with combs completely packed with brood at different stages of development. Adult bees covering every comb should accompany this; 25,000 adult bees in total are desired. Additionally, there must be two honeycombs in each colony[46]. When there are at least 100 foragers entering or departing the colony every minute through its entrance, the colony will be able to provide adequate pollination services[28−46].

Introduction and removal of beehives

The identification of a suitable food source (bee flora) is an essential step before moving the bee colonies. However, the dominance of species at the new location changes their foraging behavior. Colonies should only be moved to crops that require pollination once they have started blooming substantially. The colonies should be relocated to the target crop when bloom is between 5%–10%. That gives sufficient time for foragers to focus their attention on collecting pollen and nectar from new bee flora. The crop may not be adequately pollinated if there are too many flowers blooming, which must be averted. A few colonies can be moved to the crop at the start of flowering and the remainder after additional flowers have bloomed.

In cucurbit fields, honeybee colonies should be deployed about a week after the first staminate flowers bloom[48]. Honey bees can become unproductive if they are introduced too early because they can develop flight paths to more plentiful and appealing food sources, such as wildflowers and divert towards non-target bee flora. Additionally, the leasing costs for growers of cucurbits rise each day that beehives are on the field. The introduction of honey bee colonies into fields must be timed precisely; if it is postponed for a few days, there won't be enough pollinators to support the very first fruit-producing blooms that emerge on plants. Reyes-Carrillo et al.[48] reported that for melons, each day that honey bee hives are delayed from being introduced into a field results in a loss of 3.17 tonnes of fruit per hectare (or 7.16% of the total yield). Insufficient pollination and fruit set results in a reduction in the weight, size, and number of melon fruit.

Bee colonies are removed from fields based on whether a cucurbit crop has reached its maximum yield potential. Few researchers recommended removing honey bee colonies from melons 28 d after the first hermaphrodite flowers appeared[48], but Bratsch[49] recommended removing honey bee colonies from calabash gourds between 6 and 8 weeks following their introduction to a field.

Beehive densities

For cultivated cucurbits, various honeybee hive densities per hectare have been recommended[14−28]. The pollination of the cucurbit plant can be influenced by several factors, including the amount and species of the wild pollinators visiting flowers, the number of the open flowers, the number of the bees in the behives which is actually and actively foraging, the number of bees per day per hour pollinating the cucurbit plant and the attractiveness of the non specific crops and wild flowers[37].

The honey bee population can be affected by many factors:

(1) Due to the subsequent reutilization of the bee colonies without a recovery period.

(2) Climatic conditions.

(3) The timing of the pesticide application.

(4) Amounts and application frequency of the pesticides[47].

The honeybee densities for many of the cucurbit and cole crops that are grown in the open field are shown in Table 3. The suggested honey bee hives per hectare for some crops like the Monoceious cucumbers require 2.5 honey bee hives per hectare, while for the seeded watermelon and sponge gourd melon are 4.5 and 4 bee hives per hectare. The gynoecious cucumber and seedless watermelon require 7.5 to more than 9 honey bee hive densities per hectare. Overall, 3–5 colonies/hectare distributed evenly across the crop are advised. It is generally advised to have 2.5 colonies per hectare, but this will depend on a variety of factors, including the abundance of the flowers, their attraction, and rival pollinators.

Distribution and field placement

Consideration must also be given to the placement of the honeybee hives on the field. The honey bees' visitation to the flower also depends upon the distance between the flower and

Table 3. Summary of pollination management of different crops.

Vegetable crop	Blooming period of the crop	No. of *A. mellifera* colonies (ha)	No. of *A. cerana* colonies (ha)	Time of placement of colonies
Cabbage (*Brassica oleracea* var. *capitata*)	February–March	5	8–10	10%–15% flowering
Carrot (*Daucus carota*)	March–April	5–8	10–12	10%–15% flowering
Cauliflower (*Brassica oleracea* var. *botrytis*)	March–April	5	8–10	10%–15% flowering
Cucumber (*Cucumis sativus*)	June–September	1 for monoecious; 8 for dioecious	2–3 for monoecious; 12–16 for dioecious	10%–15% flowering
Pumpkin (*Cucurbita pepo*)	June–September	5–8	10–12	10%–15% flowering
Okra (*Abelmoschus esculentus*)	June–September	1–2	2–3	10%–15% flowering
Radish (*Raphanus sativus*)	March–April	2–3	4–6	10%–15% flowering
Turnip (*Brassica rapa* subsp. *rapa*)	February–March	2–3	4–6	5%–10% flowering

Adapted from Abrol[26].

its colonies. If the distance is less, they will forage easily, and ultimately will recruit other foragers to seek the floral resources in the flower and it will lead to more visitation of the flower per day[50]. Hence, better pollination efficiency is achieved in cucurbit and cole crops when the bee hives are near the crop. It would be better if the honeybee hives were distributed at the edge of the field, about 30 to 50 m from the first crop row.

In contrast to honey bee hives positioned along one side of the field, Mussen & Thorp[51] proposed that 10 to 20 hives spread 160 m apart around the field's margins would be preferable. To ensure that honey bees are evenly spread across a field planted for pollination purposes, an even better placement technique is to introduce the recommended number of beehives for each target vegetable crop per hectare. Additionally, colonies should have access to clean water close to the hive area and some kind of shade to prevent bees from interrupting their foraging activity to undertake hive maintenance tasks, which could otherwise have a detrimental effect on the total pollination service that is performed[28].

Focusing on the effects that bees have on crop quality will allow researchers to gather more comprehensive information about how bees might change the chemistry of specific crops.

General considerations to be taken into account for bee pollination in cross-pollinated vegetables

Pesticide application

The pesticide application should be carried out before the placement of the beehives.

Use selective pesticides and avoid pesticides with a prolonged residual period.

A pesticide application is not permitted during the pollination period unless it is necessary due to a catastrophe. The beekeeper must be consulted before using any pesticides.

Whenever a pesticide is to be sprayed, it must be done in the evening, right after dusk, when the majority of bees are inside the beehives, in consultation with the beekeeper. If necessary, advanced safety measures must be implemented, including covering the hives, locking them, or even removing them from the field if at all possible.

To prevent harm to bees that could be foraging in neighboring fields, the producer should attempt to collaborate with neighbors about pest control in their crops.

Bee pollination for seed production of vegetables

Open field conditions

The beekeeper must ensure all the necessary requirements before transferring bee colonies to the field. Each beehive in an open field should contain at least 10 bee-populated frames, of which seven should contain brood; the requirements are less stringent for early flowering crops such as oilseed rape (*Brassica napus*), for which seven bee-populated frames (four of which contain brood) are the standard.

If the crop flowers during the swarming period of bees, the colony shouldn't be oversized unless proper handling and inspection can be carried out to avert the swarming.

The majority of the bees remain in the hive during dusk, dawn, or at night; then only the beekeeper should move the hives to the field.

Usually, around 30% of the hives should be set up initially. As blooming advances, the remaining stock of the bee hives should be placed in the field a few days later. The majority of the bee hives should be kept in the field during the initial introduction of the crops or varieties with a pollination duration of seven days or less.

The flowers of *Brassica* species typically provide a lot of nectar, so the hives shouldn't be supplied with sugar syrup. In carrots, cross-pollination happens more often than self-pollination because the stamens in each flower and umbel ripen a few days before the stigma becomes receptive. Along with pollen, the bloom also makes nectar.

The nectar and pollen that the carrot flower produces are occasionally insufficient for optimum colony growth. For the establishment of bumble bee colonies, sugar syrup and pollen are provided.

Male and female/hermaphrodite flowers are present on the same plant in the cucumber, melon, and squash. Only male and hermaphrodite flowers produce pollen; nectar is produced by both types of blooms. The presence of pollen grains on the stigma of the female/hermaphrodite flower can be used to confirm bee visits.

The cucumber and particularly the squash flower, produce an abundance of nectar, so sugar syrup is not given to the beehives.

The pollinated crops' nectar production is generally influenced by irrigation. For pollinators to visit throughout the pollination time, enough irrigation is necessary. It is advised to employ ground irrigation because top irrigation (sprinkler, pivot, etc.) interferes with pollinator activities and could reduce the viability of pollen and stigma.

Greenhouse/net house

In confined conditions with a total area of less than 500 m^2, a small colony (nucleus) may be introduced. These hives (around five bee frames, three with brood) may have smaller numbers of adults and larvae than beehives in open places.

Colonies should only be relocated during the day since the older foragers will not adapt to their new surroundings and will succumb to death outside the hive. The greater part of foragers could be left at the original apiary, where fresh foragers will begin to forage in the constrained area and older ones will revert to the colonies the beekeeper had left in place to serve as hosts for them.

There must always be sufficient space for collecting honey.

The use of greenhouse coverings that imbibe or disperse UV light (wavelengths between 320 and 380 nm) should be avoided.

Honey bees typically do not harvest pollen from certain crops, such as cucumber (*Cucumis sativus*), and melon (*Cucumis melo*). Therefore, it is important to regularly monitor the pollen reserves within the beehives (at least every two weeks). If there is a pollen shortage, alternatives or pollen supplements must be given.

The bees should constantly have access to drinking water. The most highly suggested technique is to place a container of water with floating objects in it or to immerse a clean piece of burlap in the water so that bees may stand while drinking[17].

Challenges for bee pollination

Pollination is an evolutionary mutualistic process connecting pollinator insects and plants which is essential to agricultural production. However, pollination is a system that is under threat everywhere, from intensive agriculture to remote wilderness. Pesticides have a negative impact on pollinators, with insecticides killing them directly and herbicides indirectly by diminishing the pollinator flora. Pollination in natural areas and agricultural areas has declined due to the destruction of pollinator habitats. Honey bee diseases pose a threat to affect the demographics of beekeeping and the availability of bees for pollination. To conserve the biodiversity of pollinators, it is necessary to support wild pollinators, domesticate underutilized potential pollinators, and explore the environment in an eco-friendly manner. Managed, as well as wild bees that are actively involved in the pollination of crops directly or indirectly, face different challenges like colony collapse disorder, adverse effects of pesticides, habitat loss, extreme weather conditions, loss of genetic diversity, etc. (Fig. 2).

Colony collapse disorder (CCD)

Researchers from several countries are still looking into the origins of CCD at this time. The current opinion is that there are several contributing variables to this syndrome and it cannot be described by a particular cause. The disease CCD is under investigation by researchers in many parts of the world. The most often reported contributing factors of CCD are: (1) Commonly found infections and pests in beekeeping, such as tracheal mites, chalkbrood, *Nosema microsporidian*, American and European foulbrood, and small hive beetles. (2) Improper management of honey bees, such as stress brought on by increased pollination voyage and congested apiaries. (3) Use of pesticides in bee colonies that are excessive or unnecessary. (4) Queen source (devoid of the genetic diversity and the inbreeding between the queens which makes the bees more susceptible to the diseases). (5) Improper diets (scarcity of pollen and nectar with low nutritional value). (6) Overuse of pesticides harms the physiological condition of bees. (7) Overuse of chemicals on bee colonies. (8) *Varroa destructor* mites and similar pathogens. (9) Increased virulence of the existing pathogens. (10) Coordination of the two or more aforementioned hypotheses[52,53].

Pesticides and pollination services in vegetables

Honey bees gathering nectar and pollen in agrochemical-contaminated flowers may succumb to death instantly (lethal effect) or undergo physiological and behavioral alterations that will have an impact on the bee colony as a whole and adversely affect the pollination abilities (sublethal effect)[54]. Pesticides have a sublethal effect on honey bees because they limit their foraging activity and adversely affect their immunity, which lowers colony survival and pollination services. Neonicotinoids have an adverse effect on the bee colonies and some enzymatic activities that have an impact on physiological functions such as olfactory learning, taste perception, memory, and motor activities, which cause issues with orientation and navigation. Insecticides have an impact on the immune systems of bees, leaving them more vulnerable to infections like *Nosema microsporidian*[54]. These insecticides mixed with some fungicides make them more hazardous to bees.

The sublethal effects of pesticides on the honey bees reduce their immunity and foraging activity hence it lowers the colony survival and ultimately affects the pollination services. Insecticides affect the immune system of the bees making them more susceptible to pathogens like *Nosema microsporidian*[54]. To lessen the death rate of bees and reduce the risk of pesticide contamination, the introduction of bee colonies only during blooming and the removal of the colony after fruit set is done in many places. If pesticide application is necessary, then use chemicals that are less hazardous to honey bees and apply them mostly in the late afternoon or early evening when there are fewer honey bee visitors on flowers. Another possible way to protect the honey bees from pesticide application is to cover the hives with moistened clothes (e.g., burlap sacks). If the cloth consistently remains moist, it will provide a water source for the honey bees for a period of up to 2 d[54]. Pesticide poisoning must be prevented to maintain the fitness of honey bee colonies[48]. For crop protection, it is best to use biopesticides, biocontrol agents, and/or plant secondary metabolites, which are generally safer and won't harm pollinating bees[16,55–57].

Increased cost of bee pollination services

The additional costs associated with maintaining high population levels in honeybee colonies and the effort required to recover from substantial colony losses have resulted in many beekeepers moving away from the business of offering pollination services[58]. As there are fewer beekeepers, there are fewer

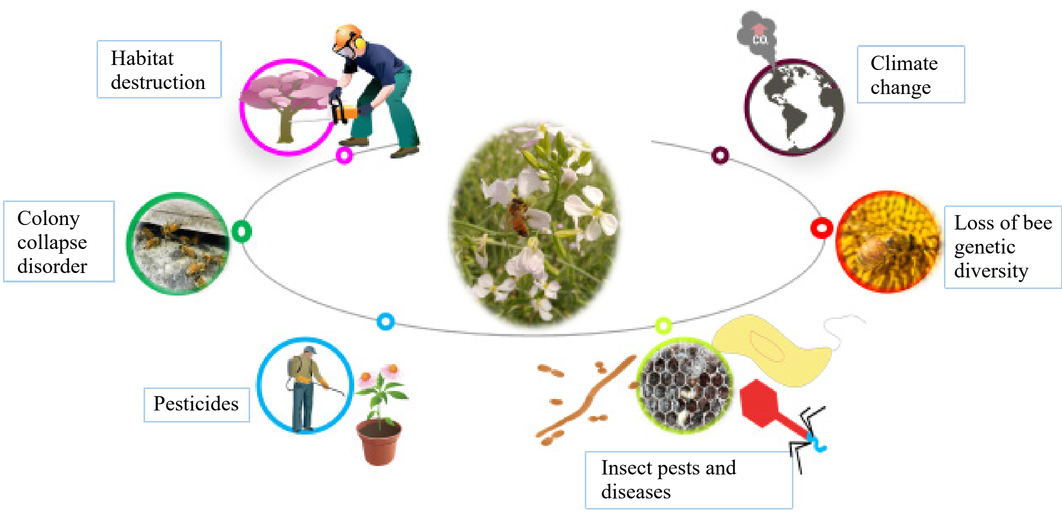

Fig. 2 Challenges for bee pollination in vegetables.

beehives available to rent for commercial crop pollination services. As a result, honeybee pollination rental costs have surged more than three times in recent years. These costs are typically determined by several factors, including the distance between the beekeeper's base of operations and the field where crop pollination services are required, the number of hives necessary, the length of time the crop is in bloom, the number of days the crop is in the field, the nutrition of the nectar and pollen it produces, and the quantity and price of honey the crop might produce for the beekeepers. The pollination costs of cross-pollinated vegetables are comparable to those of other pollination-dependent crops.

Habitat destruction

The fragmentation and degradation of habitats are causing fluctuations in pollinator statistics[59]. Due to the restriction of gene flow and increased danger of population and species extinction, these acts lead to genetic degradation[60]. According to Naug[61], pathogens and stress on honeybees because of habitat loss and diminishing foraging resources can lead to colony collapse. The number of bees, especially honeybee populations, can be negatively impacted by habitat fragmentation and degradation because of the loss or segregation of essential resources for feeding and nesting[62]. Pollinators, such as honey bees, have suffered due to habitat degradation as the percentage of semi-natural regions has declined[63].

Climate change

Changes in the climate have a significant impact on bee populations. Previous records of high, usually unexplained honeybee mortality have been linked to extended periods of cold, rain, and heat[64]. Climate may be important for colony productivity since warmer temperatures tend to reduce the metabolic demands on foragers, which increases colony output[65]. Enhanced nectar production is linked to prolonged periods of high temperatures and enough rainfall[66], which results in increased colony productivity[67]. The hard, cold winter is found to be the primary cause of colony mortality[68].

Loss of genetic diversity

A single queen's multiple matings with different males is the source of the genetic variability in honeybees (polyandry). Genetic diversity has been demonstrated to be crucial for disease resistance, homeostasis, thermoregulation, and general colony fitness at the level of the individual colony[69]. Five evolutionary lineages include the approximately 26 subspecies and several ecotypes of western honey bees (*Apis mellifera*) that have been characterized based on behavior, morphology, and genetic data. O is from the Eastern Mediterranean and the Near and Middle East, Y is from Ethiopia in East Africa, C is from Eastern Europe and the Northern Mediterranean, M is from Northern and Western Europe, and A is from Africa[70]. There may be apicultural interest in how well colonies perform in terms of various resistance features against pests, parasites, and pathogens[71]. Recent studies have introduced and assessed other features linked to colony health, such as cleanliness behavior, mite infestation development, and overwintering ability, which are increasingly bringing the development of traits associated with colony strength into focus. The loss of colonies may be caused by a lack of genetic variety since the likelihood of disease transmission increases when colonies are genetically identical and spread out over large distances[68].

Mitigation strategies to overcome the challenges faced by bees

Floral resources for conservation of bee colonies under harsh environmental conditions

The primary reason for the decline in bee populations is thought to be the loss and degradation of habitats that support nesting, especially those that provide suitable floral food resources like nectar and pollen[72,73]. Therefore, a better understanding of the significance of various landscape-level floral resource availability descriptors (e.g., floral abundance and diversity) in their contribution to sustaining wild bee pollinators during different times of the year is a prerequisite for successful bee conservation in agroecosystems[74]. For honey bee conservation, the provision of a steady supply of flower resources is essential. The usefulness of *Antigonon leptopus* Hook. & Arn, an attractive creeper, as a long-term bee forage plant was assessed. The four main native honey bee species that are drawn to it are *Apis cerana*, *Apis florea*, *Apis dorsata*, and *Tetragonula iridipennis*. The Indian bee, *A. cerana*, and the wild little bee, *A. florea*, were the two most important foragers. Both ecological and aesthetic requirements are satisfied by this plant, which is easy to multiply from seeds and cuttings. Promoting evergreen bee flora such as Antigonon will aid in the conservation of honey bee populations in both urban and natural environments. Antigonon may be used as a possible bio-indicator of the honey bee population in a particular habitat because it attracts all kinds of honey bees all year round[75]. High-quality forage supplies for pollinators could be provided *via* seed mixes based on commercially available species that thrive in nutrient-enriched soils[76]. New seed mixes that are complementary to one another in terms of their temporal persistence in grassland swards must be developed. Certain non-legume forbs, for instance, may eventually outcompete short-lived legumes due to their superior persistence.

Habitat restoration, safer pesticides and ecological approaches for protecting bees

Recent large-scale losses of honeybee colonies in many parts of the world have been mostly attributed to pollution, new diseases, and food scarcity[77]. These losses are challenging the sustainability of beekeeping. Over 30% of annual colony deaths are not uncommon in several parts of the world[78]. In addition to these losses, beekeepers confront several technical and financial difficulties due to a broad range of variations in honey production[79]. Recurrent and significant colony losses[80] not only pose a serious threat to bees but also heighten efforts to provide a sustainable beekeeping sector and, consequently, pollination services for several crop systems. Additionally, as recreational beekeeping is closely associated with raising public awareness of environmental protection, the disappearance of this ancient practice may have an effect on the availability of bee products. Nevertheless, no tool exists to evaluate the sustainability of the systems used for beekeeping at present or in the future[81].

To adjust to global climate changes, beekeeping techniques must undergo significant modifications, and technological support must be strengthened. Supporting beekeepers with better Varroa mite control techniques and avoiding losses from excessive infestation levels is particularly crucial. The majority of *Apis mellifera* colonies are infected with the Varroa mite, which can be fatal if left untreated[82]. Besides food supplements or colony transhumance, adjustments to beekeeping techniques are also necessary to offset resource limitations[83]. Beekeepers can estimate the impact of sudden changes in environments on colony productivity and manage colony transhumance by using monitoring equipment[84]. Increased local floral resources for bees would be beneficial for both honeybees and wild bees[85].

Diseases, viruses, and predators that threaten bee health have proliferated globally as a result of the global exchange market, particularly about honeybees[83]. As a result, the use of chemical treatments to combat new pests has intensified, increasing economic and environmental expenses and depreciating products like royal jelly, honey, and wax. This emphasises the necessity of (1) studying the risk of bee exchanges in order to develop regulations, and (2) developing new pest management techniques, such as integrated pest management, in order to prevent or minimize the emergence of pest resistance and to use fewer chemicals. Additionally, populations that are naturally resistant to pests, such as Varroa, should be identified and selected[86].

Bees and beekeepers need to adjust quickly due to the ongoing climate change and its impact on resource availability. In that scenario, the broad range of local and regional adaptations that honey bee populations naturally possess to different climatic conditions and patterns of resource availability[87] may serve as a valuable resource for beekeepers seeking to adapt. Beekeepers may prefer importing foreign ecotypes[83] if local genetically native bees are well-adapted to their current biotopes[88,89], but exhibit slow environmental adaptability.

Increased usage of agro-chemicals due to agricultural intensification raises the possibility of habitat degradation within agrosystems and the ensuing disruption of the environment. For example, insecticides (even at sublethal concentrations) can reduce bee diversity and abundance locally, cause behavioral impairments, kill bees, and reduce their reproductive success[90−93]. In contrast, herbicides and fertilizers can indirectly affect bees by reducing the availability of floral resources[94,95].

Enhancing habitat in agricultural systems (e.g., introducing large grasslands and flower strips) has been demonstrated to have favorable effects on wild bee population and richness, which allays concerns about the reduction in resource availability and biodiversity[96]. To create habitats that are as supportive to bee populations, data must be collected on the nutritional requirements of bees and the nutrient composition of flowers in addition to assessing the attractiveness of these new agricultural habitats[97,98]. To ascertain the sustainability of bee populations in these newly created habitats, data on life-history parameters and bee health will then be required as assessment endpoints[99]. Recent research suggests that drawing bees to these resource hotspots may have detrimental effects on bee health, including an increase in parasite prevalence and transmission[100], as well as pesticide exposure since wildflowers could be contaminated with pesticides[101]. Consequently, to decrease the use of pesticides, efforts should also be made to identify and remove plant species linked to high pathogen transmission from these artificial habitats[102]. In addition, ecosystems (resource and shelter) that support insect pollinator bees and insect natural enemies should be established. In fact, for ecological engineering techniques like planting wildflower strips and other habitat restorations to be successful, there needs to be a concurrent decrease in pesticide use to save pollinators and naturally occurring beneficial insects. Furthermore, newly planned habitats should incorporate plant species with multiple floral phenology to lengthen the blooming period, since climate change is likely to worsen changes in floral resource phenology related to land use and consequently plant-pollinator mismatches[103]. Because wildflowers help sustain bee populations over time, their sustainability in agro-systems would also benefit crops pollinated by bees.

When considering resource management in agro-systems, the quality of resources provided by crops has often been neglected, although it is well-known that nectar composition can affect bee attraction and fidelity[104] and may influence the severity of pathogen infections[105,106] . Furthermore, a recent investigation revealed how crop domestication affects the chemistry of floral rewards, which may lead to increased pathogen infection in bumblebees[107]. Thus, it is important to comprehend how profitable crops are for bees and create crop breeding initiatives to enhance floral nutritional resources and crop–pollinator interactions[105]. This is especially significant in light of the climate change and increasing atmospheric CO_2 levels, which have been shown to lower the protein concentration of floral pollen, a resource that is crucial for bee growth[108].

Improving bee habitats by creating artificial pastures may be appealing to bees, but there is still work to be done to take into account for the needs of bee habitats, mitigate any unfavorable side effects, and finally create a stable colony of bees. In this regard, restoring, and safeguarding natural and semi-natural habitats may be more effective and dependable options for fostering resource diversity and sustainability, which will eventually improve bee health, as they naturally increase bee abundance and richness[109]. Before wintering, it was discovered that semi-natural habitats were twice as good at enhancing honeybee health as artificial bee pastures[99]. This implies that, rather than being a substitute management strategy, habitat augmentation should be viewed as a means of assisting habitat restoration or preservation. There is an urgent need to restore bees access to food supplies and habitat through ecological intensification (diversified farming systems) and by harmonizing the conservation of wild and managed bee pollinators in a sustainable manner. Financial assistance for applied research and development will enable scientific beekeeping, and bee pollination to create management techniques for productive vegetable ecosystems to ensure food security as well as nutritional security.

Hazards involved with managed pollinators for crop pollination

A major threat linked to pollinator management is introducing an alien pollinator species for crop pollination, which may later become invasive[110]. The following are some of the ways that native species and ecosystems may be impacted by introduced (but also native) controlled pollinators and their trade: (1) exploitative or interfering competition for floral resources and nesting locations[111], (2) inefficient pollination of native plants, which alters native plant reproduction[112], (3) unintentional pollination of exotic plants[113], (4) the introduction of diseases or parasites into wild or native populations, including the simultaneous introduction of natural enemies[114], and (5) genetic introgression or disruption of native pollinator species' reproductive processes[115]. When managed pollinators become superabundant, they may negatively affect crop yields and wild plant reproduction[110]. For example, fruit set was negatively impacted by high rates of visits by the invasive *Bombus terrestris* to commercial raspberries in Patagonia[116]. Risk assessments should be carried out before the introduction of a non-native pollinator species, particularly because managed species may significantly harm native pollinators[110]. However, the number of manageable pollinator species has increased over time, indicating the possibility or perceived necessity of more appropriate pollinator species. These may have been selected based on characteristics such as their capacity to buzz-pollinate (as in the instance of tomato pollination) or build their nests close to a crop being produced in the field. Crop-pollinator networks may be used to determine which flowers frequently visit a certain crop in conjunction with measuring the pollinator efficiency of the species or closely related species that share similar qualities (e.g., short-tongued vs long-tongued bumble bees) to achieve successful trait-matching. The identification of native species using trait matching could help prioritize research and evaluate the threats that managed species represent to other native pollinators and their ecosystems if they become invasive.

Enhancing and/or managing multiple native pollinator species makes sense given the potential risks associated with pollinator management and the fact that a combination of species provides better pollination assurance than a single species[117]. One way to do this would be to create habitats for native pollinators in or around crop fields. Protecting and restoring favorable habitats, raising the value and quantity of floral resources, cutting back on intensive mechanical practices, cutting back on chemical inputs, and providing pollinator nest sites are all goals of habitat enhancement to benefit pollinator abundance and diversity in agricultural landscapes[118]. Moreover, habitat may be deliberately constructed to support targeted bee and non-bee pollinators for increased pollination by combining information of the most effective pollinators of certain crops with knowledge of their lifecycle requirements[119]. These methods strengthen and support native wild pollinator populations, which in turn increases pollination of nearby crops[120].

Integrated crop pollination

Apis mellifera is an efficient pollinator of several plants[28] but not necessarily the most practical, so the capabilities of wild species of native bees are now being increasingly appreciated in crop pollination[121]. A few bee species have traits that make it possible to manage them for use as agricultural pollinators[122], providing alternatives for specific crops or serving as co-pollinators of honeybees. For maintaining consistent and sustained crop pollination, these insect-mediated diverse pollination sources offer the opportunity to combine wild and managed pollinators[123].

The farmland owners have scant knowledge of bee pollination to decide the best and most efficient ways to assist wild and managed pollinators for crop pollination. The local or regional farming system, which includes its pollination system, the degree of pest management, the available funds, and the bee species that are practical to align with and integrate into the agricultural production system, must all be taken into consideration when making decisions about bee pollination. Because agricultural pollination is complex, decision-support systems are necessary for producers and other land managers to provide reliable pollination for stable and sustainable crop production[124].

To offer consistent and reasonably priced crop pollination, integrated crop pollination uses managed pollinator species in combination with farming practices that boost, maintain, and protect pollinator populations[124]. No one strategy will be the best option for every location where a crop is grown due to variations in the degree of a crop's reliance on pollinators, managed and wild bee populations, crop variety, regional economics of production, horticultural practices, and individual preferences.

Conclusions

Insect pollination is a crucial component of agriculture with significant economic repercussions. Increased productivity in cross-pollinated vegetables, especially cucurbits and cole crops, has been made possible by the management of different pollinator species. Though several pollinator species are reported, only honey bees and bumble bees are intently explored in cross-pollinated vegetables with honey bees being the most significant. Pollinator-dependent crops are becoming more and more important to agriculture, and this trend toward crops grown permanently under protected cultivation is probably due to customer demand for pollination-dependent vegetables. The availability of pollinators for crops that need pollination services, including cucurbits and cole crops, have drastically decreased as a result of managed honey bee numbers dropping in recent years. Natural pollinators can occasionally aid in agricultural pollination, but they often have low densities and are unable to establish large field populations to adequately pollinate a crop. As a result, both controlled and wild insect pollinators are in poor health and anything that lowers their populations would undoubtedly affect the output of cucurbits, cole crops, and other farming systems where fruit set is dependent on pollinators. There is a problem with food security and farmer livelihoods because only a few species of bees are typically used for pollination. The most popular managed pollinator, *A. mellifera* colonies, have high mortality rates. As a result, it is necessary to protect wild pollinators, for example by managing land in a way that is sensitive to them, and to take into account a wider range of managed pollinator species. Crop-specific and sustainable management of a diversity of new pollinator species may help to protect future crop yields and food security, even though the deployment and management of novel pollinator species is not without risks, especially if used in areas where a pollinator is non-native.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Divekar PA; draft manuscript preparation & revision: Divekar PA, Mishra A; language editing and manuscript review: Divekar PA, Mishra A, Kumar R. All authors reviewed the results and approved the final version of the manuscript.

Data availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Acknowledgments

The authors thank Achuit Kumar Singh, Principal Scientist and Suhas G. Karkute, Scientist, ICAR-Indian Institute of Vegetable Research, Varanasi, for providing valuable feedback to improve the quality of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

Dates

Received 15 May 2024; Revised 17 August 2024; Accepted 7 September 2024; Published online 29 October 2024

References

1. Welbaum GE. 2015. Vegetable History, Nomenclature, and Classification. In *Vegetable production and practices. IARC handbooks of cancer prevention: Fruit and vegetables*. Wallingforth, Oxfordshire, UK: CAB International. pp. 1–15
2. Pennington JAT, Fisher RA. 2009. Classification of fruits and vegetables. *Journal of Food Composition and Analysis* 22:S23–S31
3. Septembre-Malaterre A, Remize F, Poucheret P. 2018. Fruits and vegetables, as a source of nutritional compounds and phytochemicals: Changes in bioactive compounds during lactic fermentation. *International Food Research Journal* 104:86–99
4. Partap T. 2001. Mountain agriculture, marginal land and sustainable livelihoods: Challenges and opportunities. *International Symposium on Mountain Agriculture in HKH Region, 21–24 May 2001*. ICIMOD, Kathmandu, Nepal. https://lib.icimod.org/record/21882/files/c_attachment_127_968.pdf
5. Divekar PA, Majumder S, Rani V, Pandey KK, Behera TK. 2022. Helping agriculture through helpful honey bees. In *Compendium for Winter School on "Underexploited Vegetables: Unexplored Treasure Trove for Food, Nutritional and Economic Security"*. pp. 391–99. www.researchgate.net/publication/362013465_Helping_Agriculture_through_Helpful_Honey_bees
6. Giannini TC, Cordeiro GD, Freitas BM, Saraiva AM, Imperatriz-Fonseca VL. 2015. The dependence of crops for pollinators and the economic value of pollination in Brazil. *Journal of Economic Entomology* 108(3):849–57
7. Robinson WS, Nowogrodzki R, Morse RA. 1989. The value of honey bees as pollinators of US crops, part II. *American Bee Journal* 129:411–423,477–487
8. Gallai N, Salles JM, Settele J, Vaissière BE. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics* 68:810–21
9. Mishra RC. 1997–98. *Perspectives in Indian apiculture*. New Delhi: Agro. Botanica, HS Offset Printers. 188 pp.
10. Walters SA, Taylor BH. 2006. Effects of honey bee pollination on pumpkin fruit and seed yield. *HortScience* 41:370–73
11. Divekar PA, Nebapure S, Majumder S, Verma CK. 2021. *Honeybee and crop-pollination*. https://vikaspedia.in/agriculture/best-practices/sustainable-agriculture/biodiversity/honeybee-andcrop-pollination (Accessed on 30 July 2022)
12. Chandra A, Sujayanand GK, Revanasidda, Bandi SM, Angami T, et al. 2022. Insect Pollinators and Hybrid Seed Production: Relevance to Climate Change and Sustainability. In *Plant Male Sterility Systems for Accelerating Crop Improvement*, eds. Bohra A, Parihar AK, Naik SJS, Chandra A. Singapore: Springer. pp. 265–83. doi: 10.1007/978-981-19-3808-5_12
13. Kevan PG. 2007. *Bees: Biology & Management*. Cambridge, Ontario, Canada: Enviroquest Ltd. 345 pp.
14. Free JB. 1993. *Insect Pollination of Crops*. London, UK: Academic Press. 684 pp.
15. Negi N, Sharma, A, Chadha S, Sharma PC, Sharma P, et al. 2020. Role of pollinators in vegetable seed production. *Journal of Entomology and Zoology Studies* 8(5):417–22
16. Divekar PA, Narayana S, Divekar BA, Kumar R, Gadratagi BG, et al. 2022. Plant secondary metabolites as defense tools against herbivores for sustainable crop protection. *International Journal of Molecular Sciences* 23(5):2690
17. Gabai A, Vaissière BE, Blacquiere T, Freitas BM, Allsopp M, et al. 2018. *Protocol for using pollinators in hybrid seed production: an outline for improving pollinator*. www.worldseed.org/wp-content/uploads/2018/03/Pollination_Guide_20180316_Final.pdf
18. Gray AR. 1982. Taxonomy and evolution of broccoli (*Brassica oleracea* var. *italica*). *Economic Botany* 36(4):397–410
19. Divekar PA, Patel SK, Manimurugan C. and Singh V. 2023. Insect pollinator diversity and their foraging behaviour in Radish, *Raphanus sativus* L. *Emergent Life Sciences Research* 9(2):68–76
20. Divekar PA, Singh K, Verma CK, Rai AB, Singh B, et al. 2023. Assessment of bee flora and development of a floral calendar in relation to pharmaceutical potential of honey and bee pollen in Eastern Uttar Pradesh, India. *Annals of Phytomedicine* 12:844–55
21. Divekar PA, Singh K, Yadav S, Manimurugan C, Patel SK, et al. 2023c. Diversity and foraging behaviour of insect pollinators in Cauliflower. *Ecology Environment & Conservation* 29(2):971–78
22. Bohart GE, Todd FE. 1961. Pollination of seed crops by insects. In *Seeds. The Yearbook of Agriculture*. Washington DC: US Government Printing Office. pp. 240–46
23. Klein AM, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, et al. 2007. Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B* 274:303–13
24. de Siqueira KMM, Kiill LHP, da Silva Gama DR, dos Santos Araújo DC, de Souza Coelho M. 2011. Comparison of the flowering and visitation patterns of yellow melon in Juazeiro-BA. *Revista Brasileira de Fruticultura* 33:473–78
25. Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, et al. 2013. Wild pollinators enhance fruit set of crops regardless of honey-bee abundance. *Science* 339:1608–11
26. Abrol DP. 2012. Honeybee and Crop Pollination. In *Pollination Biology*. Dordrecht, Netherlands: Springer. pp. 85–110. doi: 10.1007/978-94-007-1942-2_5
27. Verma LR, Partap U. 1994. Foraging behaviour of *Apis cerana* on cauliflower and cabbage and its impact on seed production. *Journal of Apicultural Research* 33:231–36
28. Delaplane KS, Mayer DF. 2000. *Crop Pollination by Bees*. Cambridge, UK: CABI. 344 pp. doi: 10.1079/9780851994482.0000
29. Dafni A, Kevan PG, Husband BC. 2005. *Practical Pollination Biology*. Cambridge, Ontário, Canada: Enviroquest. 590 pp.
30. Winston ML. 1987. *The Biology of the Honey Bee*. Cambridge, MA: Harvard University Press. 281 pp.
31. Slaa EJ, Sánchez Chaves LA, Malagodi-Braga KS, Hofstede FE. 2006. Stingless bees in applied pollination: Practice and perspectives. *Apidologie* 37:293–315
32. Winfree R, Williams NM, Dushoff J, Kremen C. 2007. Native bees provide insurance against ongoing honey bee losses. *Ecology Letters* 10:1105–13
33. DeGrandi-Hoffman G. 2003. Honey bees in U.S. agriculture: past, present, and future. In *For nonnative crops, whence pollinators of the future?* eds. Strickler K, Cane JH. Lanham, Maryland: Entomological Society of America. pp. 11–20. doi: 10.4182/zsgh5376.2003.11
34. Allsopp MH, de Lange WJ, Veldtman R. 2008. Valuing insect pollination services with cost of replacement. *PLoS ONE* 3:e3128

35. Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, et al. 2010. Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution* 25:345−53
36. Cane JH, Sampson BJ, Miller SA. 2011. Pollination value of male bees: The specialist bee *Peponapis pruinosa* (Apidae) at summer squash (*Cucurbita pepo*). *Environmental Entomology* 40:614−20
37. Woodcock TS. 2012. *Pollination in the agricultural landscape: best management practices for crop pollination*. Guelph, Ontario, Canada: University of Guelph. 113 pp.
38. Winfree R, Williams NM, Gaines H, Ascher JS, Kremen C. 2008. Wild bee pollinators provide the majority of crop visitation across land-use gradients in New Jersey and Pennsylvania, USA. *Journal of Applied Ecology* 45:793−802
39. Bezerra ADdM. 2014. Use of straw bee (*Scaptotrigona* sp. nov.) At the pollination of melon (*Cucumis melo* L.) in greenhouse. Dissertação de mestrado (Mestrado em Zootecnia), Universidade Federal do Ceará, Fortaleza, Brazil. 91 pp. www.repositorio.ufc.br/handle/riufc/17097
40. De Luca PA, Vallejo-Marín M. 2013. What's the 'buzz' about? The ecology and evolutionary significance of buzz-pollination. *Current Opinion in Plant Biology* 16:429−35
41. Del Sarto MCL, Peruquetti RC, Campos LAO. 2005. Evaluation of the neotropical stingless bee *Melipona quadrifasciata* (Hymenoptera: Apidae) as pollinator of greenhouse tomatoes. *Journal of Economic Entomology* 98:260−66
42. Dos Solange ABS, Roselino AC, Bego LR. 2008. Pollination of Cucumber *Cucumis sativus* L. (Cucurbitales: Cucurbitaceae), by the stingless bees *Scaptotrigona* aff. *depili* Moure and *Nannotrigona testaceicornis* Lepeletier (Hymenoptera: Meliponini) in greenhouses. *Neotropical Entomology* 37:506−12
43. Azmi WA, Samsuri N, Mohd Hatta MF, Ghazi R, Seng CT. 2017. Effects of stingless bee (*Heterotrigona itama*) pollination on greenhouse cucumber (*Cucumis sativus*). *Malaysian Applied Biology* 46:51−55
44. Azmi WA, Wan Sembok WZ, Yusuf N, Mohd Hatta MF, Salleh AF, et al. 2019. Effects of pollination by the indo-Malaya stingless bee (Hymenoptera: Apidae) on the quality of greenhouse- produced rockmelon. *Journal of Economic Entomology* 112:20−24
45. Sadeh A, Shmida A, Keasar T. 2007. The carpenter bee *Xylocopa pubescens* as an agricultural pollinator in greenhouses. *Apidologie* 38:508−17
46. Sagili RR, Burgett DM. 2011. Evaluating honey bee colonies for pollination: A guide for growers and beekeepers. Pacific Northwest Extension Publication No. 623. Corvallis, OR: Oregon State University. 8 pp.
47. Bomfim IGA. 2013. Use of stingless bees (Meliponinae: Apidae) in greenhouse For pollination and fruit production of seeded and seedless mini watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai]. Tese (Doutorado em Zootecnia), Universidade Federal do Ceará, Fortaleza, Brazil. 142 pp.
48. Reyes-Carrillo JL, Cano-Ríos P, Nava-Camberos U. 2009. Optimum pollination period in the muskemelon with honey bees (*Apis mellifera* L.). *Agricultura Técnica en México* 35:370−77
49. Bratsch A. 2009. Specialty crop profile: Ornamental gourds. Publication 438-101. Virginia Cooperative Extension, Virginia Polytechnic Institute and State University, Blacksburg. 6 pp. www.uky.edu/ccd/sites/www.uky.edu.ccd/files/gourds.pdf (Accessed on 5th August 2022)
50. Jay SC. 1986. Spatial management of honey bees on crops. *Annual Review of Entomology* 31:49−65
51. Mussen EC, Thorp RW. 1997. *Honey bee pollination of cantaloupe, cucumber and watermelon*. Publication 7224. University of California, Cooperative Extension, Division of Agriculture and Natural Resources, Davis, CA. doi: 10.3733/ucanr.7224
52. Ellis JD, Evans JD, Pettis J. 2010. Colony losses, managed colony population decline and colony collapse disorder in the United States. *Journal of Apicultural Research* 49:134−36
53. Fairbrother A, Purdy J, Anderson T, Fell R. 2014. Risks of neonicotinoid insecticides to honeybees. *Environmental Toxicology and Chemistry* 33:719−31
54. Freitas BM, Pinheiro JN. 2012. *Polinizadores e Pesticidas: Princípios de manejo para os ecossistemas brasileiros*. 1st Edition. Brasília, Brazil: Ministério do Meio Ambiente. 112 pp.
55. Dukare A, Paul S, Mhatre PH, Divekar PA. 2021. Biological Disease Control Agents in Organic Crop Production System. In *Pesticide Contamination in Freshwater and Soil Environs: Impacts, Threats, and Sustainable Remediation*. USA: Apple Academic Press. doi: 10.1201/9781003104957-10
56. Dukare AS, Paul S, Asha AD, Nivetha N, Aggarwal C, et al. 2021. Role of bacterial and fungal chitinases in integrated management of pest and diseases of agro-horticultural crops. In *Microbes for Sustainable Insect Pest Management. Sustainability in Plant and Crop Protection*, eds. Khan MA, Ahmad W. vol 17. Cham: Springer. doi: 10.1007/978-3-030-67231-7_2
57. Shinde PG, Divekar PA, Singh DK, Pal DS, Nadaf A. 2021. Bio-pesticide management strategy for mustard aphid *Lipaphis erysimi* (Kaltenbach) (Homoptera: Aphididae). *Journal of Pharmaceutical Innovation* 10:397−400
58. Potts SG, Roberts SPM, Dean R, Marris G, Brown MA, et al. 2010. Declines of managed honey bees and beekeepers in Europe. *Journal of Apicultural Research* 49:15−22
59. Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, et al. 2004. Extinction risk from climate change. *Nature* 427:145−48
60. Barrett SCH, Kohn JR, Falk DA, Holsinger KE. 1991. Genetic and evolutionary consequences of small population size in plants: Implications for conservation. In *Genetics and conservation of rare plants*, eds. Falk DA, Holsinger KE. New York, NY: Oxford Academic. pp. 3−30. doi: 10.1093/oso/9780195064292.003.0001
61. Naug D. 2009. Nutritional stress due to habitat loss may explain recent honeybee colony collapses. *Biological Conservation* 142:2369−72
62. Cane JH, Minckley RL, Kervin LJ, Roulston TH, Williams NM. 2006. Complex responses within a desert bee guild (Hymenoptera: Apiformes) to urban habitat fragmentation. *Ecological Applications* 16:632−44
63. Kremen C, Williams NM, Bugg RL, Fay JP, Thorp RW. 2004. The area requirements of an ecosystem service: Crop pollination by native bee communities in California. *Ecology Letters* 7:1109−19
64. Kauffeld NM, Everitt JH, Taylor EA. 1976. Honey bee problems in the Rio Grande Valley of Texas. *American bee journal* 116:220−32
65. Harrison JF, Fewell JH. 2002. Environmental and genetic influences on flight metabolic rate in the honey bee, *Apis mellifera*. *Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology* 133:323−33
66. Shuel RW. 1992. The production of nectar and pollen. In *The hive and the honey bee*. Hamilton, IL: Dadant. pp. 401−36
67. Voorhies EC, Galbraith JK, Todd FE. 1933. *Economic aspects of the bee industry*. 5th Edition. Berkeley, Calif: University of California Press. doi: 10.5962/bhl.title.61191
68. Paudel Y, Mackereth R, Hanley R, Qin W. 2015. Honey bees (*Apis mellifera* L.) and pollination issues: current status, impacts and potential drivers of decline. *Journal of Agricultural Science* 7:93
69. Mattila HR, Seeley TD. 2007. Genetic diversity in honey bee colonies enhances productivity and fitness. *Science* 317:362−64
70. Sheppard WS, Meixner MD. 2003. *Apis mellifera pomonella*, a new honey bee subspecies from Central Asia. *Apidologie* 34:367−75
71. Meixner MD, Costa C, Kryger P, Hatjina F, Bouga M, et al. 2010. Conserving diversity and vitality for honey bee breeding. *Journal of apicultural research* 49:85−92
72. Potts SG, Imperatriz-Fonseca V, Ngo HT, Aizen MA, Biesmeijer JC, et al. 2016. Safeguarding pollinators and their values to human well-being. *Nature* 540:220−29
73. Scheper J, Reemer M, van Kats R, Ozinga WA, van der Linden GTJ, et al. 2014. Museum specimens reveal loss of pollen host plants

as key factor driving wild bee decline in The Netherlands. *The Proceedings of the National Academy of Sciences of the United States of America* 111:17552–57
74. Dicks LV, Showler DA, Sutherland WJ 2010. *Bee conservation: evidence for the effects of interventions*. Vol. 1. Exeter, UK: Pelagic Publishing, Exeter. 146 pp.
75. Reddy PVR. 2020. Mexican creeper, Antigonon leptopus hook. and arn: An effective bee forage plant to conserve honey bees. *Journal of Horticultural Sciences* 15(2):225–28
76. Mortimer SR, Kessock-Philip R, Potts SG, Ramsay A, Roberts SPM, et al. 2006. *Review of the diet and micro-habitat values for wildlife and the agronomic potential of selected plant species*. Technical Report. English Nature, Peterborough, UK. 204 pp. https://repository.rothamsted.ac.uk/download/97f2152c8663d24411162b8ce45863117c9fc823094ebaa7bc665a54eb923a65/1664874/r697_part_1.pdf
77. Goulson D, Nicholls E, Botías C, Rotheray EL. 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347:1255957
78. Neumann P, Carrack P. 2010. Honey bee colony losses. *Journal of Apicultural Research* 49:1–6
79. Chauzat MP, Cauquil L, Roy L, Franco S, Hendrikx P, et al. 2013. Demographics of the European apicultural industry. *PLoS One* 8:e79018
80. Kulhanek K, Steinhauer N, Rennich K, Caron DM, Sagili RR, et al. 2017. A national survey of managed honey bee 2015–2016 annual colony losses in the USA. *Journal of apicultural research* 56:328–40
81. Kouchner C, Ferrus C, Blanchard S, Decourtye A, Basso B, et al. 2019. Bee farming system sustainability: an assessment framework in metropolitan France. *Agricultural Systems* 176:102653
82. Le Conte Y, Ellis M, Ritter W. 2010. *Varroa* mites and honey bee health: can *Varroa* explain part of the colony losses? *Apidologie* 41:353–63
83. Le Conte Y, Navajas M. 2008. Climate change: impact on bee populations and their illnesses. *Revue Scientifique et Technique* 27:485–497,499–510
84. Lecocq A, Kryger P, Vejsnaes F, Bruun Jensen A. 2015. Weight watching and the effect of landscape on honeybee colony productivity: investigating the value of colony weight monitoring for the beekeeping industry. *PLoS One* 10:e0132473
85. Wratten SD, Gillespie M, Decourtye A, Mader E, Desneux N. 2012. Pollinator habitat enhancement: benefits to other ecosystem services. *Agriculture, Ecosystems & Environment* 159:112–22
86. Locke B. 2016. Natural *Varroa* mite-surviving *Apis mellifera* honeybee populations. *Apidologie* 47:467–82
87. De la Rúa P, Jaffé R, Dall'Olio R, Muñoz I, Serrano J. 2009. Biodiversity, conservation and current threats to European honeybees. *Apidologie* 40:263–84
88. Büchler R, Costa C, Hatjina F, Andonov S, Meixner MD, et al. 2014. The influence of genetic origin and its interaction with environmental effects on the survival of *Apis mellifera* L. colonies in Europe. *Journal of Apicultural Research* 53:205–14
89. Francis RM, Amiri E, Meixner MD, Kryger P, Gajda A, et al. 2014. Effect of genotype and environment on parasite and pathogen levels in one apiary - a case study. *Journal of Apicultural Research* 53:230–32
90. Henry M, Béguin M, Requier F, Rollin O, Odoux JF, et al. 2012. A common pesticide decreases foraging success and survival in honey bees. *Science* 336:348–50
91. Sanchez-Bayo F, Goka K. 2014. Pesticide residues and bees – a risk assessment. *PLoS One* 9:e94482
92. Stanley DA, Garratt MPD, Wickens JB, Wickens VJ, Potts SG, et al. 2015. Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees. *Nature* 528:548–50
93. Hladik ML, Vandever M, Smalling KL. 2016. Exposure of native bees foraging in an agricultural landscape to current-use pesticides. *Science of The Total Environment* 542:469–77
94. Decourtye A, Mader E, Desneux N. 2010. Landscape enhancement of floral resources for honey bees in agro-ecosystems. *Apidologie* 41:264–77
95. Woodcock BA, Savage J, Bullock JM, Nowakowski M, Orr R, Tallowin JRB, Pywell RF. 2014. Enhancing floral resources for pollinators in productive agricultural grasslands. *Biological Conservation* 171:44–51
96. Filipiak M. 2018. A better understanding of bee nutritional ecology is needed to optimize conservation strategies for wild bees – the application of ecological stoichiometry. *Insects* 9:85
97. Moerman R, Vanderplanck M, Fournier D, Jacquemart AL, Michez D. 2017. Pollen nutrients better explain bumblebee colony development than pollen diversity. *Insect Conservation and Diversity* 10:171–79
98. Vaudo AD, Tooker JF, Grozinger CM, Patch HM. 2015. Bee nutrition and floral resource restoration. *Current Opinion in Insect Science* 10:133–41
99. Alaux C, Allier F, Decourtye A, Odoux JF, Tamic T, et al. 2017. A 'Landscape physiology' approach for assessing bee health highlights the benefits of floral landscape enrichment and semi-natural habitats. *Scientific reports* 7:40568
100. Piot N, Meeus I, Kleijn D, Scheper J, Linders T, et al. 2019. Establishment of wildflower fields in poor quality landscapes enhances micro-parasite prevalence in wild bumble bees. *Oecologia* 189:149–58
101. Botías C, David A, Horwood J, Abdul-Sada A, Nicholls E, et al. 2015. Neonicotinoid residues in wildflowers, a potential route of chronic exposure for bees. *Environmental Science & Technology* 49:12731–40
102. Adler LS, Michaud KM, Ellner SP, McArt SH, Stevenson PC, et al. 2018. Disease where you dine: plant species and floral traits associated with pathogen transmission in bumble bees. *Ecology* 99:2535–45
103. Havens K, Vitt P. 2016. The importance of phenological diversity in seed mixes for pollinator restoration. *Natural Areas Journal* 36:531–37
104. Prasifka JR, Mallinger RE, Portlas ZM, Hulke BS, Fugate KK, et al. 2018. Using nectar-related traits to enhance crop-pollinator interactions. *Frontiers in Plant Science* 9:812
105. Manson JS, Otterstatter MC, Thomson JD. 2010. Consumption of a nectar alkaloid reduces pathogen load in bumble bees. *Oecologia* 162:81–89
106. Richardson LL, Adler LS, Leonard AS, Andicoechea J, Regan KH, et al. 2015. Secondary metabolites in floral nectar reduce parasite infections in bumblebees. *Proceedings of the Royal Society of London Series B, Biological Sciences* 282:20142471
107. Egan PA, Adler LS, Irwin RE, Farrell IW, Palmer-Young EC, et al. 2018. Crop domestication alters floral reward chemistry with potential consequences for pollinator health. *Frontiers in Plant Science* 9:1357
108. Ziska LH, Pettis JS, Edwards J, Hancock JE, Tomecek MB, et al. 2016. Rising atmospheric CO_2 is reducing the protein concentration of a floral pollen source essential for North American bees. *Proceedings of the Royal Society of London Series B, Biological Sciences* 283:20160414
109. Tonietto RK, Larkin DJ. 2018. Habitat restoration benefits wild bees: A meta-analysis. *Journal of Applied Ecology* 55(2):582–590
110. Russo L, de Keyzer CW, Harmon-Threatt AN, LeCroy KA, MacIvor JS. 2021. The managed-to-invasive species continuum in social and solitary bees and impacts on native bee conservation. *Current Opinion in Insect Science* 46:43–49
111. Ropars L, Dajoz I, Fontaine C, Muratet A, Geslin B. 2019. Wild pollinator activity negatively related to honey bee colony densities in urban context. *PLoS One* 14:e0222316
112. Valido A, Rodríguez-Rodríguez MC, Jordano P. 2019. Honeybees disrupt the structure and functionality of plant-pollinator networks. *Scientific Reports* 9:4711

113. Morales C, Saez A, Arbetman MP, Cavallero L, Aizen MA. 2014. Detrimental effects of volcanic ash deposition on bee fauna and plant-pollinator interactions. *Ecología Austral* 24:42−50
114. Schmid-Hempel R, Eckhardt M, Goulson D, Heinzmann D, Lange C, et al. 2014. The invasion of southern South America by imported bumblebees and associated parasites. *Journal of Animal Ecology* 83:823−37
115. Kraus FB, Szentgyörgyi H, Rożej E, Rhode M, Moroń D, et al. 2011. Greenhouse bumblebees (*Bombus terrestris*) spread their genes into the wild. *Conservation genetics* 12:187−92
116. Aizen MA, Arbetman MP, Chacoff NP, Chalcoff VR, Feinsinger P, et al. 2020. Invasive bees and their impact on agriculture. *Advances in Ecological Research* 63:49−92
117. Garibaldi LA, Carvalheiro LG, Leonhardt SD, Aizen MA, Blaauw BR, et al. 2014. From research to action: enhancing crop yield through wild pollinators. *Frontiers in Ecology and the Environment* 12:439−47
118. Kleijn D, Bommarco R, Fijen TPM, Garibaldi LA, Potts SG, et al. 2019. Ecological intensification: bridging the gap between science and practice. *Trends in Ecology & Evolution* 34:154−66
119. Howlett BG, Todd JH, Willcox BK, Rader R, Nelson WR, et al. 2021. Using non-bee and bee pollinator - plant species interactions to design diverse plantings benefiting crop pollination services. *Advances in Ecological Research* 64:45−103
120. Forbes SJ, Northfield TD. 2017. Increased pollinator habitat enhances cacao fruit set and predator conservation. *Ecological Applications* 27:887−99
121. Winfree R, Gross BJ, Kremen C. 2011. Valuing pollination services to agriculture. *Ecological Economics* 71:80−88
122. Mader E, Spivak M, Evans E. 2010. *Managing Alternative Pollinators: A Handbook for Beekeepers, Growers, and Conservationists*. SARE Handbook 11, NRAES Publication 186. www.sare.org/wp-content/uploads/Managing-Alternative-Pollinators.pdf
123. Kevan PG, Clark EA, Thomas VG. 1990. Insect pollinators and sustainable agriculture. *American Journal of Alternative Agriculture* 5:13−22
124. Isaacs R, Williams N, Ellis J, Pitts-Singer TL, Bommarco R, et al. 2017. Integrated crop pollination: combining strategies to ensure stable and sustainable yields of pollination-dependent crops. *Basic and Applied Ecology* 22:44−60
125. Bhardwaj DR, Singh A, Singh U. 2013. Genetic variability of bottle gourd [*Lagenaria siceraria* (Mol.) Standl.] by multivariate analysis. *Proceeding of National Symposium on Abiotic and Biotic Stress management in Vegetable Crops*. Indian Society of Vegetable Science. 370 pp.
126. Revanasidda Belavadi VV. 2019. Floral biology and pollination in *Cucumis melo* L., a tropical andromonoecious cucurbit. *Journal of Asia Pacific Entomology* 22(1):215−25
127. Prasannakumar, NR, Parkash C, Kumar KP. 2015. Role of pollinators in Broccoli seed production. *Pest Management in Horticultural Ecosystems* 21(2):187−89
128. Divija SD, Kamala Jayanthi P, Varun YB, Saravan Kumar P, Krishnarao G, et al. 2022. Diversity, abundance and foraging behaviour of insect pollinators in Radish (*Raphanus raphanistrum* subsp. *Sativus* L.). *Journal of Asia-Pacific Entomology* 25(2):101909