© 2023, Centre for Advanced Research in Agricultural Sciences
Research Journal of Agricultural Sciences
Volume 14; Issue 01; pp 072–079

Open Access
ISSN: 0976-1675 (P)
ISSN: 2249-4538 (E)

Research Review

Role of Pollinators in Plant Reproduction and Food Security: A Concise Review

Hemanta Saha[1], Sandipan Chatterjee[2] and Anirban Paul*[3]

[1-3] Department of Botany, Suri Vidyasagar College, Suri - 731101, Birbhum, West Bengal, India

Abstract
Pollination can increase the yield, quality and stability of fruit and seed crops. Animal pollination plays an important role in sexual reproduction and the successful pollination of many crops. Inadequate pollination not only reduces yield, but can also affect yield and produce a high percentage of poor-quality fruit. Most of our crops are poorly adapted to biotic and abiotic stresses such as disease, pests, drought, salinity and the constant introduction of new adaptive genes lead to preserve crop diversity and enhance pollination. Pesticides kill pollinators directly, and herbicides kill pollinators indirectly by reducing what they eat. Habitat destruction has reduced pollination in agricultural and natural areas. Pollinator numbers are believed to be declining worldwide, resulting in reduced yields in some crops, ultimately impact on food production and food security.

***Key words*:** Pollination, Stress, Pesticide, Yield, Food Security

Pollination is the transfer of pollen from a male part of a plant to a female part of a plant, later enabling fertilization and the production of seeds, most often by an animal or by wind. Pollinating agents are animals such as insects, birds, and bats; water; wind; and even plants themselves, when self-pollination occurs within a closed flower. Pollination often occurs within a species. When pollination occurs naturally as well as by plant breeders in between species it can produce hybrid offspring [1]. In angiosperms, after the pollen grain has landed on the stigma, it germinates and develops a pollen tube which grows down the style until it reaches an ovary. Sperm cells from the pollen grain then move along the pollen tube, enter an ovum cell through the micropyle and fertilize it, resulting in the production of a seed.

A successful angiosperm pollen grain (gametophyte) containing the male gametes is transported to the stigma, where it germinates and its pollen tube grows down the style to the ovary. Its two gametes travel down the tube to where the gametophyte(s) containing the female gametes are held within the carpel. One nucleus fuses with the polar bodies to produce the endosperm tissues (3n), and the other with the egg cell (female gamete) to produce the embryo (2n). Thus, the phenomenon is called double fertilization [2-3]. In gymnosperms, the ovule is not contained in a carpel, but exposed on the surface of a dedicated support organ, such as the scale of a cone, so that the penetration of carpel tissue is not needed here. Details of the process vary according to the division of gymnosperms in question. Two main modes of fertilization are found in gymnosperms. Cycads and Ginkgo have motile sperm that swim directly to the egg inside the ovule, whereas conifers and Gnetophyres have sperm, that are unable to swim but are conveyed to the egg along a pollen tube [4].

The study of pollination brings together many disciplines, such as botany, horticulture, entomology and ecology. The pollination process as an interaction between flower and pollen vector was first addressed in the 18th century by Christian Konrad Sprengel. It is important in horticulture and agriculture, because fruiting is dependent on fertilization: the result of pollination. The study of pollination by insects is known as anthecology [5]. Pollination can increase the yield, quality and stability of fruit and seed crops. Animal pollination has important role in sexual reproduction and successful pollination of many crops. Another value of pollination lies in its effect on quality and efficiency of crop production. Inadequate pollination can result not only in reduced yields but also affect the yield and produced high percentage of inferior fruits [6].

Process

Pollen germination has three stages; hydration, activation and pollen tube emergence. The pollen grain is severely dehydrated so that its mass is reduced enabling it to be more easily transported from flower to flower. Germination only takes place after rehydration, ensuring that premature germination does not take place in the anther. Hydration allows

Received: 02 Nov 2022; Revised accepted: 24 Dec 2022; Published online: 09 Jan 2023

Correspondence to: Anirban Paul, Department of Botany, Suri Vidyasagar College, Suri - 731 101, Birbhum, West Bengal, India, Tel: +91 8918772207; E-mail: ourpublications2022@gmail.com

Citation: Saha H, Chatterjee S, Paul A. 2023. Role of pollinators in plant reproduction and food security: A concise review. *Res. Jr. Agril Sci*. 14(1): 72-79.

the plasma membrane of the pollen grain to reform into its normal bilayer organization providing an effective osmotic membrane. Activation involves the development of actin filaments throughout the cytoplasm of the cell, which eventually become concentrated at the point from which the pollen tube will emerge. Hydration and activation continue as the pollen tube begins to grow [7].

In conifers, the reproductive structures are borne in the form of cones. The cones are either pollen cones (male) or ovulate cones (female), but some species are monoecious and others dioecious. A pollen cone contains hundreds of microsporangia carried on (or borne on) reproductive structures called sporophylls. Spore mother cells in the microsporangia divide by meiosis to form haploid microspores that develop further by two mitotic divisions into immature male gametophytes (pollen grains). The four resulting cells consist of a large tube cell that forms the pollen tube, a generative cell that will produce two sperm by mitosis, and two prothallial cells that degenerate. These cells comprise a very reduced microgametophyte, that is contained within the resistant wall of the pollen grain [8-9].

The pollen grains are dispersed by the wind to the female, ovulate cone that is made up of many overlapping scales (megasporophylls), each protecting two ovules, each of which consists of a megasporangium (the nucellus) wrapped in two layers of tissue, the integument and the cupule, that were derived from highly modified branches of ancestral gymnosperms. When a pollen grain lands close enough to the tip of an ovule, it is drawn in through the micropyle often by means of a drop of liquid known as a pollination drop [10]. The pollen enters a pollen chamber close to the nucellus, and there it may wait for a year before it germinates and forms a pollen tube that grows through the wall of the megasporangium (nucellus) where fertilization takes place. During this time, the megaspore mother cell divides by meiosis to form four haploid cells, three of which degenerate. The surviving one develops as a megaspore and divides repeatedly to form an immature female gametophyte (egg sac). Two or three archegonia containing an egg then develop inside the gametophyte. Meanwhile, in the spring of the second year two sperm cells are produced by mitosis of the body cell of the male gametophyte. The pollen tube elongates and pierces and grows through the megasporangium wall and delivers the sperm cells to the female gametophyte inside. Fertilization takes place when the nucleus of one of the sperm cells enters the egg cell in the megagametophyte's archegonium [9].

In flowering plants, the anthers of the flower produce microspores by meiosis. These undergo mitosis to form male gametophytes, each of which contains two haploid cells. Meanwhile, the ovules produce megaspores by meiosis, further division of these form the female gametophytes, which are very strongly reduced, each consisting only of a few cells, one of which is the egg. When a pollen grain adheres to the stigma of a carpel it germinates, developing a pollen tube that grows through the tissues of the style, entering the ovule through the micropyle. When the tube reaches the egg sac, two sperm cells pass through it into the female gametophyte and fertilization takes place [8].

Methods

Pollination may be biotic or abiotic. Biotic pollination relies on living pollinators to move the pollen from one flower to another. Abiotic pollination relies on wind, water or even rain. About 80% of angiosperms rely on biotic pollination (Fig 1) [11].

Abiotic

Abiotic pollination uses nonliving methods such as wind and water to move pollen from one flower to another. This allows the plant to spend energy directly on pollen rather than on attracting pollinators with flowers and nectar.

By wind

98% of abiotic pollination is anemophily i.e., pollination by wind. This probably arose from insect pollination, most likely due to changes in the environment or the availability of pollinators [12-14]. The transfer of pollen is more efficient than previously thought; wind pollinated plants have developed to have specific heights, in addition to specific floral, stamen and stigma positions that promote effective pollen dispersal and transfer (Fig 1) [15].

By water

Pollination by water, hydrophily, uses water to transport pollen, sometimes as whole anthers; these can travel across the surface of the water to carry dry pollen from one flower to another [16]. In *Vallisneria spiralis*, an unopened male flower floats to the surface of the water, and, upon reaching the surface, opens up and the fertile anthers project forward. The female flower, also floating, has its stigma protected from the water, while its sepals are slightly depressed into the water, allowing the male flowers to tumble in (Fig 1) [16].

By rain

Rain pollination is used by a small percentage of plants. Heavy rain discourages insect pollination and damages unprotected flowers, but can itself disperse pollen of suitably adapted plants, such as *Ranunculus flammula*, *Narthecium ossifragum*, and *Caltha palustris* [17]. In these plants, excess rain drains allowing the floating pollen to come in contact with the stigma [17]. In rain pollination in orchids, the rain allows for the anther cap to be removed, allowing for the pollen to be exposed. After exposure, raindrops causes the pollen to be shot upward, when the stipe pulls them back, and then fall into the cavity of the stigma. Thus, for the orchid *Acampe rigida*, this allows the plant to self-pollinate, which is useful when biotic pollinators in the environment have decreased (Fig 1) [18].

Switching methods

It is possible for a plant have varying pollination methods, including both biotic and abiotic pollination. The orchid *Oeceoclades maculata* uses both rain and butterflies, depending on its environmental conditions [19].

Biotic

Pollinator

More commonly, pollination involves pollinators (also called pollen vectors): organisms that carry or move the pollen grains from the anther of one flower to the receptive part of the carpel or pistil (stigma) of another flower [20]. Between 100,000 and 200,000 species of animal act as pollinators of the world's 250,000 species of flowering plant [21]. The majority of these pollinators are insects, but about 1,500 species of birds and mammals visit flowers and may transfer pollen between them. Besides birds and bats which are the most frequent visitors, these include monkeys, lemurs, squirrels and rodents (Fig 1) [21].

Entomophily, pollination by insects, often occurs on plants that have developed colored petals and a strong scent to attract insects such as, bees, wasps and occasionally ants (Hymenoptera), beetles (Coleoptera), moths and butterflies

(Lepidoptera), and flies (Diptera) (Fig 2). The existence of insect pollination dates back to the dinosaur era [22].

In zoophily, pollination is performed by vertebrates such as birds and bats, particularly hummingbirds, sunbirds, spider hunters, honey eaters and fruit bats. Ornithophily or bird pollination is the pollination of flowering plants by birds. Chiropterophily or bat pollination is the pollination of flowering plants by bats (Fig 1). Plants adapted to use bats or moths as pollinators typically have white petals, strong scent and flower at night, whereas plants that use birds as pollinators tend to produce copious nectar and have red petals [23]. Insect pollinators such as honeybees (*Apis* spp.) [24] bumblebee (*Bombus* spp.) [25-26] and butterflies (e.g., *Thymelicus flavus*) [27] have been observed to engage in flower constancy, which means they are more likely to transfer pollen to other conspecific plants [28-29]. This can be beneficial for the pollinators, as flower constancy prevents the loss of pollen during interspecific flights and pollinators from clogging stigmas with pollen of other flower species. It also improves the probability that the pollinator will find productive flowers easily accessible and recognizable by familiar clues (Fig 2) [30].

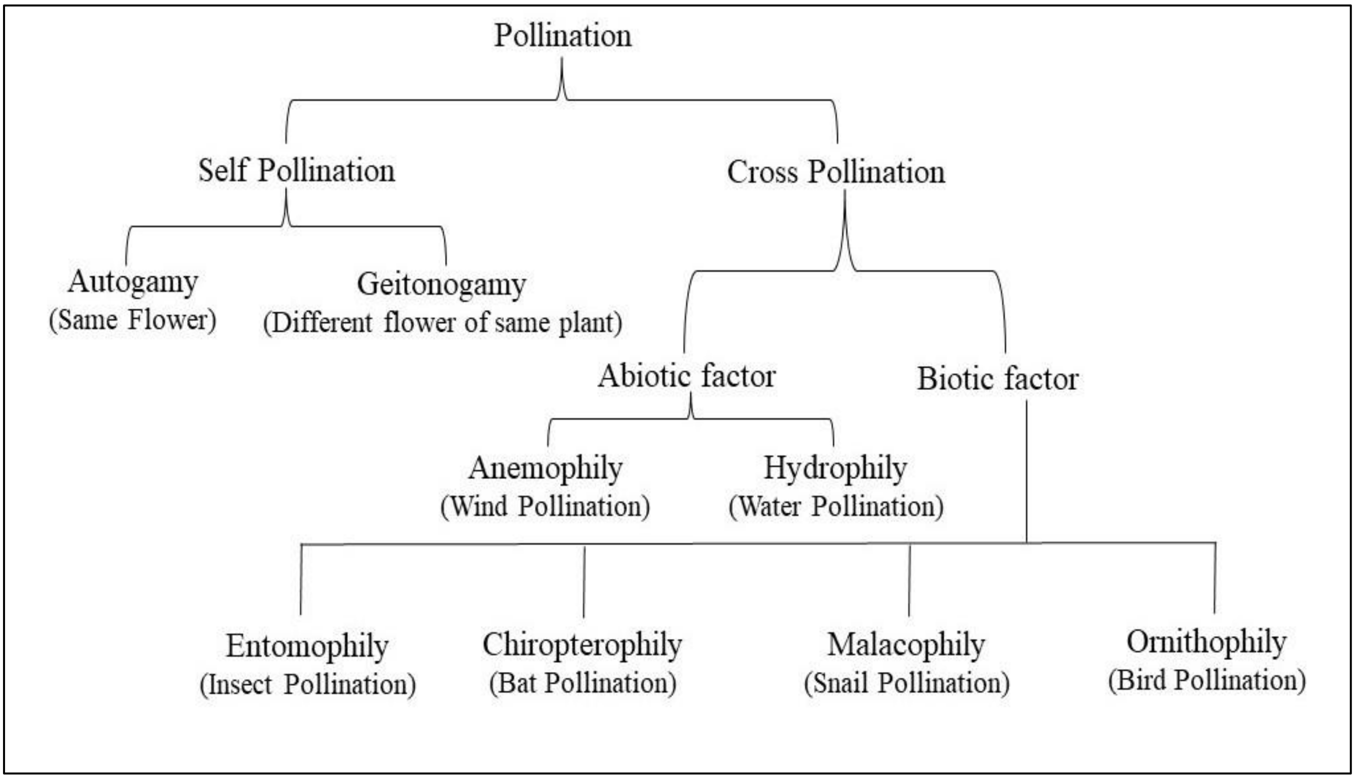

Fig 1 Different type of pollination

Some flowers have specialized mechanisms to trap pollinators to increase effectiveness [31]. Other flowers will attract pollinators by odor. For example, bee species such as *Euglossa cordata* are attracted to orchids this way, and it has been suggested that the bees will become intoxicated during these visits to the orchid flowers, which last up to 90 minutes [32]. However, in general, plants that rely on pollen vectors tend to be adapted to their particular type of vector, for example day-pollinated species tend to be brightly coloured, but if they are pollinated largely by birds or specialist mammals, they tend to be larger and have larger nectar rewards than species that are strictly insect-pollinated (Fig 2). They also tend to spread their rewards over longer periods, having long flowering seasons; their specialist pollinators would be likely to starve if the pollination season were too short [31].

As for the types of pollinators, reptile pollinators are known, but they form a minority in most ecological situations. They are most frequent and most ecologically significant in island systems, where insect and sometimes also bird populations may be unstable and less species-rich. Adaptation to a lack of animal food and of predation pressure, might therefore favour reptiles becoming more herbivorous and more inclined to feed on pollen and nectar [33]. Most species of lizards in the families that seem to be significant in pollination seem to carry pollen only incidentally, especially the larger species such as Varanidae and Iguanidae, but especially several species of the Gekkonidae are active pollinators, and so is at least one species of the Lacertidae, *Podarcis lilfordi*, which pollinates various species, but in particular is the major pollinator of *Euphorbia dendroides* on various Mediterranean islands [34].

Mammals are not generally thought of as pollinators, but some rodents, bats and marsupials are significant pollinators and some even specialize in such activities. In South Africa certain species of *Protea* (in particular *Proteahumi flora*, *P. amplexicaulis*, *P. subulifolia*, *P. decurrens* and *P. cordata*) are adapted to pollination by rodents (particularly Cape Spiny Mouse, *Acomyssubspinosus*) [35] and elephant shrews (*Elephantulus* species) [36]. The flowers are borne near the ground, are yeasty smelling, not colourful, and sunbirds reject the nectar with its high xylose content. The mice apparently can digest the xylose and they eat large quantities of the pollen [37]. In Australia pollination by flying, gliding and earthbound mammals has been demonstrated [38]. Examples of pollen vectors include many species of wasps that transport pollen of many plant species, being potential or even efficient pollinators [39].

Mechanism

Pollination can be accomplished by cross-pollination or by self-pollination

Cross-pollination, also called allogamy, occurs when pollen is delivered from the stamen of one flower to the stigma of a flower on another plant of the same species [8]. Plants adapted for cross-pollination have several mechanisms to prevent self-pollination; the reproductive organs may be arranged in such a way that self-fertilization is unlikely, or the stamens and carpels may mature at different times [8].

Self-pollination (Fig 1) occurs when pollen from one flower pollinates the same flower or other flowers of the same individual [40]. It is thought to have evolved under conditions when pollinators were not reliable vectors for pollen transport, and is most often seen in short-lived annual species and plants that colonize new locations [41]. Self-pollination may include autogamy, where pollen is transferred to the female part of the same flower; or *geitonogamy*, when pollen is transferred to another flower on the same plant (Fig 1) [42]. Plants adapted to self-fertilize often have similar stamen and carpel lengths. Plants that can pollinate themselves and produce viable offspring are called self-fertile. Plants that cannot fertilize themselves are called self-sterile, a condition which mandates cross-pollination for the production of offspring [42].

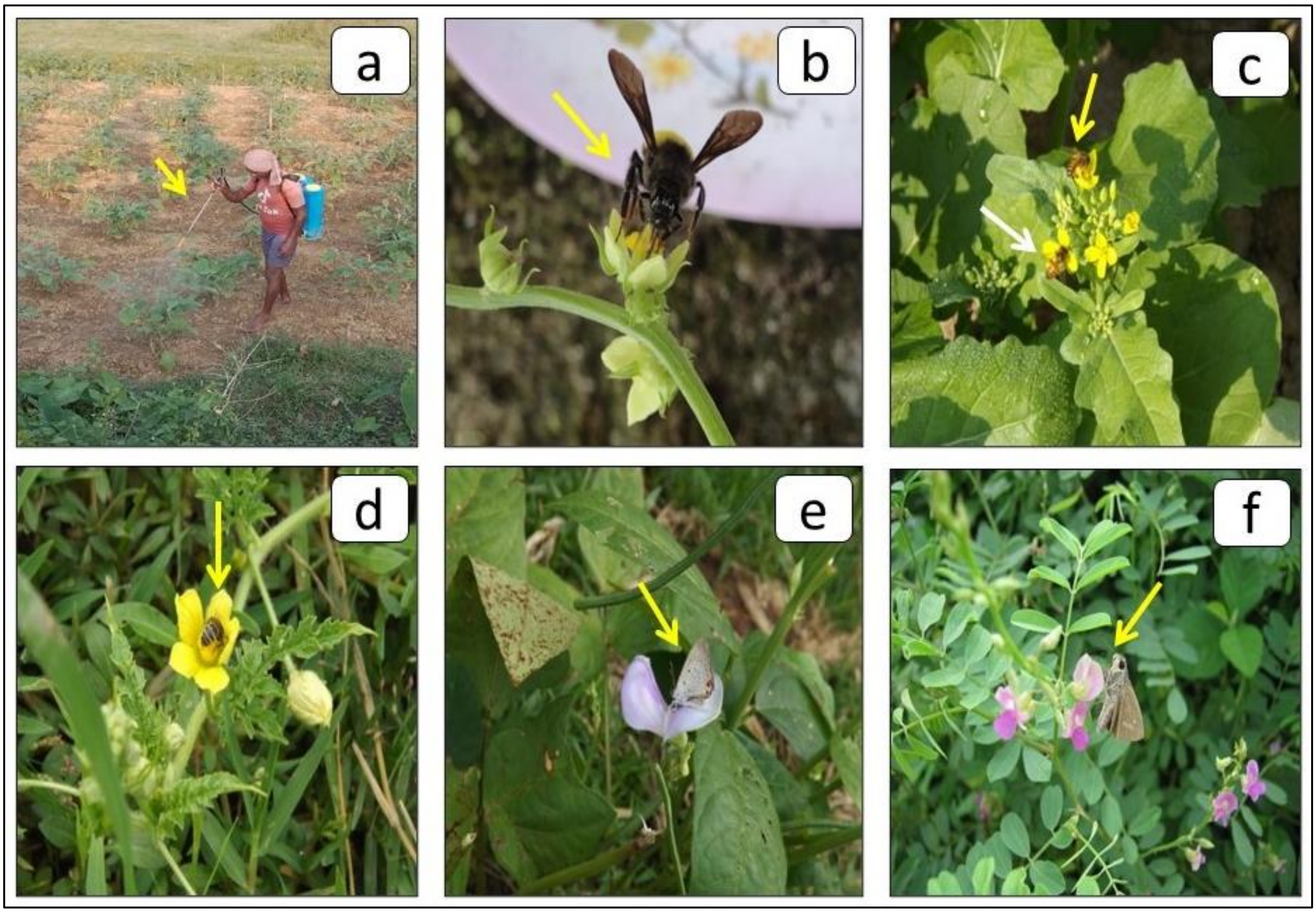

Fig 2 Insect pollination and food security

(a). Spraying of pesticide on crop field, (b). Visiting of *Xylocopa* as pollinator on flower, (c). Visiting of *Apis spray* as pollinator on flower, (d). Visiting of A*migella* as pollinator on flower, (e). Visiting of *Borbo* as pollinator on flower, (f). Visiting of *Lycebean* as pollinator on flower

Cleistogamy is self-pollination that occurs before the flower opens. The pollen is released from the anther within the flower or the pollen on the anther grows a tube down the style to the ovules. It is a type of sexual breeding, in contrast to asexual systems such as apomixis. Some cleistogamous flowers never open, in contrast to chasmogamous flowers that open and are then pollinated. Cleistogamous flowers are by necessity found on self-compatible or self-fertile plants [43]. Although certain orchids and grasses are entirely cleistogamous, other plants resort to this strategy under adverse conditions. Often there may be a mixture of both cleistogamous and chasmogamous flowers, sometimes on different parts of the plant and sometimes in mixed inflorescences. The ground bean produces cleistogamous flowers below the ground, and mixed cleistogamous and chasmogamous flowers above the ground [44].

Pollination syndrome

The first fossil record for abiotic pollination is from fern-like plants in the late Carboniferous period. Gymnosperms show evidence for biotic pollination as early as the Triassic period. Many fossilized pollen grains show characteristics similar to the biotically dispersed pollen today. Furthermore, the gut contents, wing structures, and mouthpart morphology of fossilized beetles and flies suggest that they acted as early pollinators. The association between beetles and angiosperms during the early Cretaceous period led to parallel radiations of angiosperms and insects into the late Cretaceous. The evolution of nectaries in late Cretaceous flowers signals the beginning of the mutualism between hymenopterans and angiosperms [45-46].

Bees provide a good example of the mutualism that exists between hymenopterians and angiosperms. Flowers provide bees with nectar (an energy source) and pollen (a source of protein). When bees go from flower to flower collecting pollen, they are also depositing pollen grains onto the flowers, thus pollinating them. While pollen and nectar, in most cases, are the most notable reward attained from flowers, bees also visit flowers for other resources such as oil, fragrance, resin and even waxes [47]. It has been estimated that bees originated with the origin or diversification of angiosperms [48]. In addition, cases of coevolution between bee species and flowering plants have been illustrated by specialized adaptations. For example, long legs are selected for in *Redivivan eliana*, a bee that collects oil from *Diascia capsularis*, which have long spur lengths that are selected for in order to deposit pollen on the oil-collecting bee, which in turn selects for even longer legs in *R. neliana* and again longer spur length in *D. capsularis* is selected for, thus, continually driving each other's evolution [49].

Pollination management is a branch of agriculture that seeks to protect and enhance present pollinators and often involves the culture and addition of pollinators in monoculture situations, such as commercial fruit orchards. The largest managed pollination event in the world is in Californian almond orchards, where nearly half (about one million hives) of the US honey bees are trucked to the almond orchards each spring. New York's apple crop requires about 30,000 hives; Maine's blueberry crop uses about 50,000 hives each year. The US solution to the pollinator shortage, so far, has been for commercial beekeepers to become pollination contractors and to migrate. Just as the combine harvesters follow the wheat harvest from Texas to Manitoba, beekeepers follow the bloom from south to north, to provide pollination for many different crops [50].

In America, bees are brought to commercial plantings of cucumbers, squash, melons, strawberries, and many other crops. Honey bees are not the only managed pollinators: a few other species of bees are also raised as pollinators. The alfalfa leafcutter bee is an important pollinator for alfalfa seed in western United States and Canada. Bumblebees are increasingly raised and used extensively for greenhouse tomatoes and other crops [50].

The ecological and financial importance of natural pollination by insects to agricultural crops (Fig 2), improving their quality and quantity, becomes more and more appreciated and has given rise to new financial opportunities. The vicinity of a forest or wild grasslands with native pollinators near agricultural crops, such as apples, almonds or coffee can improve their yield by about 20%. The benefits of native pollinators may result in forest owners demanding payment for their contribution in the improved crop results – a simple example of the economic value of ecological services. Farmers can also raise native crops in order to promote native bee pollinator species as shown with *Lasioglossum vierecki* in Delaware [51] and *Lasioglossum leucozonium* in southwest Virginia [52]. The American Institute of Biological Sciences reports that native insect pollination saves the United States agricultural economy nearly an estimated $3.1 billion annually through natural crop production [53]; pollination produces some $40 billion worth of products annually in the United States alone [50-54].

Pollination of food crops has become an environmental issue, due to two trends. The trend to monoculture means that greater concentrations of pollinators are needed at bloom time than ever before, yet the area is forage poor or even deadly to bees for the rest of the season. The other trend is the decline of pollinator populations, due to pesticide misuse and overuse, new diseases and parasites of bees, clearcut logging, decline of beekeeping suburban development, removal of hedges and other habitat from farms, and public concern about bees. Widespread aerial spraying for mosquitoes due to West Nile fears is causing an acceleration of the loss of pollinators [55-59].

In some situations, farmers or horticulturists may aim to restrict natural pollination to only permit breeding with the preferred individual plants. This may be achieved through the use of pollination bags.

Environmental impacts

Loss of pollinators, also known as Pollinator decline, i.e., colony collapse disorder, has been noticed in recent years. These losses of pollinators have caused a disturbance in early plant regeneration processes such as seed dispersal and of course, pollination. Early processes of plant regeneration greatly depend on plant-animal interactions and because these interactions are interrupted, biodiversity and ecosystem functioning are threatened [60]. Pollination by animals aids in the genetic variability and diversity within plants because it allows for out-crossing instead for self-crossing. Without this genetic diversity there would be a lack of traits for natural selection to act on for the survival of the plant species. Seed dispersal is also important for plant fitness because it allows plants the ability to expand their populations. More than that, it permits plants to escape environments that have changed and have become difficult to reside in. All of these factors show the importance of pollinators for plants, which are the foundation for a stable ecosystem. If only a few species of plants depended on pollinators the overall effect would not be as devastating however, this is not the case. It is known that more than 87.5% of angiosperms, over 75% of tropical tree species, and 30-40% of tree species in temperate regions depend on pollination and seed dispersal [60].

Possible explanations for pollinator decline include habitat destruction, excessive use of pesticides, diseases and climate change [61]. It has also been found that the more destructive forms of human disturbances are land use changes such as fragmentation, selective logging, and the conversion to secondary forest habitat [60]. Defaunate of frugivores has also been found to be an important driver [62]. These alterations are especially harmful due to the sensitivity of the pollination process of plants [60]. There was a study done on tropical palms and the researchers concluded that defaunation has caused a decline in seed dispersal, which causes a decrease in genetic variability in this species [58]. Habitat destruction such as fragmentation and selective logging remove area that are most optimal for the different types of pollinators, which removes pollinators food resources, nesting sites, and leads to isolation of populations [63]. The effect of pesticides on pollinators has been debated due to the difficulty to be confident that a single pesticide is the cause and not a mixture or other threats [63]. It is also not known if exposure alone causes damages, or if the duration and potency are also factors [63]. However, insecticides have some negative effects (Fig 2a).

Food security and pollinator decline

Besides the imbalance of the ecosystem caused by the decline in pollinators, it may jeopardize food security. Though crop fields may experience a wide range of meteorological conditions over a large geographic area and different topography but pollination is necessary for plants to continue their populations and 3/4 of the world's food supply are plants that require pollinators [63, 64]. Insect pollinators, like bees, are large contributors to crop production, over 200 billion dollars' worth of crop species are pollinated by these insects (Fig 2) [63]. Pollinators are also essential because they improve crop quality and increase genetic diversity, which is necessary in producing fruit with nutritional value and various flavors [65-69]. Crops that do not depend on animals for pollination but on the wind or self-pollination, like corn and potatoes, have doubled in production and make up a large part of the human diet but do not provide the micronutrients that are needed

[70]. The essential nutrients that are necessary in the human diet are present in plants that rely on animal pollinators [70]. There have been issues in vitamin and mineral deficiencies and it is believed that if pollinator populations continue to decrease these deficiencies will become even more prominent [69].

Reports by several workers strongly suggested that decreasing yields of some crops due to declining of crop pollinators around the world [70-71]. Potential biological vector can fulfill the needs of cross- pollination [72], Bees are the most important pollinators because they feed on pollen and nectar. Investigations on efficiency of pollinators for optimal pollination, fertilization, role of insect pollinators in fruit set and yields in many agricultural and horticultural crops is carried out by different researchers [73-75]. Though the protection of native pollinator is critical, they should conserve [73], [76]. It would thus be prudent to set aside areas for native pollinators in agro-ecosystem and to encourage their population by providing forage and nesting sites for their conservation. In some recent publications scientists have alerted the general public, policy makers, planners, and also politician about the importance of pollination and pollinators, the seriousness of their demise, and urgency for their conservation [76-79].

Agriculture especially crop production is the mainstay of Indian economy which supports about millions of farmer families and Geographical Indication (GI) tag is a source of pride of any region [64]. A variety of crops are grown under diverse climatic situations in different cropping systems. India is a vast country with tropical, sub-tropical plants rich in different region. The country ranks 6th for harboring the largest number of threatened plant species. The IUCN Red list data shows 91% plant species are threatened due to habitat and inability to pollinate by proper pollinator [80]. Due to havoc uses of fertilizers, pesticides and insecticides the pollinators are coming down to maximum reduction in their total population and become an issue of major concern around the world [77], [80-83].

CONCLUSION

Considering the various threats to biodiversity today, better knowledge of the reproductive strategies of flowering plants, which rely heavily on flower biology, including pollination mechanisms, is of great importance. Understanding floral organization is therefore a central issue in the phylogenetic reconstruction of angiosperms at all levels. Better knowledge of phylogenetic history and animal-plant interactions is important for the development of conservation measures for future research. Detailed knowledge of flower biology, pollination, and interactions between flowers and visitors is therefore a prerequisite for fruit and seed formation and for the development of various preservation protocols.

LITERATURE CITED

1. Barrows EM. 2011. *Animal Behavior Desk Reference*. A Dictionary of Animal Behavior, Ecology, and Evolution. Third Edition. CRC Press LCC, Boca Raton, FL. pp 794.
2. Fritsch FE, S EJ. 1920. An introduction to the structure and reproduction of plants. G. Bell.
3. Mauseth JD. 2008. *Botany: An Introduction to Plant Biology*. Publisher: Jones & Bartlett, ISBN 978-0-7637-5345-0
4. Baker HG. 1983. *An Outline of the History of Anthecology, or Pollination Biology*. *In*: (Eds) Leslie Real. Pollination Biology. Academic Press. pp 8.
5. Mc Gregor SE. 1976. *Insect Pollination of Cultivated Crop Plants*. Agriculture Hand book No. 496, USDA, USA. pp 411.
6. Burd M. 1994. Bateman's principle and plant reproduction: The role of pollen limitation in fruit and seed set. *The Botanical Review* 60: 83-139.
7. Raghavan V. 1997. *Molecular Embryology of Flowering Plants*. Cambridge University Press. pp 210-216. ISBN 978-0-521-55246-2.
8. Campbell NA, Reece JB. 2002. *Biology*. (6th Edition). Pearson Education. pp 600-612. ISBN 978-0-201-75054-6.
9. Runions C, Owens JN. 1999. Sexual reproduction of interior spruce (Pinaceae). I. Pollen germination to archegonial maturation. *International Journal of Plant Sciences* 160(4): 631-640. doi:10.1086/314170.
10. Koontz SM, Weekley CW, Haller Crate SJ, Menges ES. 2017. Patterns of chasmogamy and cleistogamy, a mixed-mating strategy in an endangered perennial. *AoB Plants* 79(6): plx059. doi: 10.1093/aobpla/plx059. PMID: 29308127; PMCID: PMC5751043.
11. Ackerman JD. 2000. Abiotic pollen and pollination: Ecological, functional, and evolutionary perspectives. *Plant Systematics and Evolution* 222(1/4): 167-185. doi:10.1007/BF00984101.
12. Faegri K, Pijl L, Van D. 2013. *Principles of Pollination Ecology*. Elsevier. pp 34. ISBN 9781483293035.
13. Whitehead DR. 1969. Wind pollination in the angiosperms: Evolutionary and environmental considerations. *Evolution* 23(1): 28-35. doi:10.2307/2406479. JSTOR 2406479. PMID 28562955.
14. Culley TM, Weller SG, Sakai AK. 2002. The evolution of wind pollination in angiosperms. *Trends in Ecology and Evolution* 17(8): 361-369. doi:10.1016/S0169-5347(02)02540-5.
15. Friedman J, Barrett SCH. 2009. Wind of change: new insights on the ecology and evolution of pollination and mating in wind-pollinated plants. *Annals of Botany* 103(9): 1515-1527. doi:10.1093/aob/mcp035. PMC 2701749. PMID 19218583.
16. Cox PA. 1988. Hydrophilous pollination. *Annual Review of Ecology and Systematics* 19: 261-279. doi:10.1146/annurev.es.19.110188.001401. JSTOR 2097155.
17. Hagerup O. 1950. Rain-pollination. I kommission hos E. Munksgaard. Retrieved 26 May 2018.
18. Fan XL, Barrett SCH, Lin H, Chen LL, Zhou X, Gao JY. 2012. Rain pollination provides reproductive assurance in a deceptive orchid. *Annals of Botany* 110(5): 953-958. doi:10.1093/aob/mcs1654 .
19. Aguiar JMRBV, Pansarin LM, Ackerman JD, Pansarin ER. 2012. Biotic versus abiotic pollination in Oeceocladesmaculata (Lindl.) Lindl. (Orchidaceae). *Plant Species Biology* 27(1): 86-95. doi:10.1111/j.1442-1984.2011.00330.x.
20. Anonymous. 2015. *Types of Pollination, Pollinators and Terminology*. Crops Review. Com. Retrieved 2015-10-20.
21. Abrol DP. 2012. Non-bee pollinators-plant interaction. *Pollination Biology*. Chapter 9. pp 265-310. doi:10.1007/978-94-007-1942-2_9. ISBN 978-94-007-1941-5.
22. Anonymous. 2015. First ever record of insect pollination from 100 million years ago. *Science Daily*. Retrieved 2015-10-20.

23. Rodríguez-Gironés MA, Santamaría L. 2004. Why are so many bird flowers red? *PLoS Biology* 2(10): e306. doi:10.1371/journal.pbio.0020350. PMC 521733. PMID 15486585.
24. Hill PSM, Wells PH, Wells H. 1997. Spontaneous flower constancy and learning in honey bees as a function of colour. *Animal Behaviour* 54(3): 615-627. doi:10.1006/anbe.1996.0467.
25. Stout JC, Allen JA, Goulson D. 1998. The influence of relative plant density and floral morphological complexity on the behaviour of bumblebees. *Oecologia* 117(4): 543-550. doi:10.1007/s004420050691. PMID 28307680.
26. Chittka L, Gumbert A, Kunze J. 1997. Foraging dynamics of bumble bees: correlates of movement within and between plant species. *Behavioral Ecology* 8(3): 239-249. doi:10.1093/beheco/8.3.239.
27. Goulson D, Ollerton J, Sluman C. 1997. Foraging strategies in the small skipper butterfly, Thymelicusflavus: when to switch? *Animal Behaviour* 53(5): 1009-1016. doi:10.1006/anbe.1996.0390.
28. Harder LD, Williams NM, Jordan CY, Nelson WA. 2021. The effects of floral design and display on pollinator economics and pollen dispersal. pp 297-317. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511542268.016
29. Chittka L, Thomson JD. 2001. Cognitive ecology of pollination: Animal behavior and floral evolution. Cambridge University Press.
30. Chittka L, Thomson JD, Waser NM. 1999. Flower constancy, insect psychology, and plant evolution. *Naturwissenschaften* 86(8): 361-377. doi:10.1007/s001140050636.
31. Potts B, Gore P. 1995. Reproductive biology and controlled pollination of *Eucalyptus*. School of Plant Science, University of Tasmania.
32. Dressler RL. 1968. Pollination by Euglossine bees. *Evolution* 22 (1): 202-210. doi: 10.2307/2406664. JSTOR 2406664. PMID 28564982
33. Olesen JM, Valido A. 2003. Lizards as pollinators and seed dispersers: an island phenomenon. *Trends in Ecology and Evolution* 18(4): 177-181.
34. Godínez-Álvarez H. 2004. Pollination and seed dispersal by lizards. *Revista Chilena de Historia Natural* 77: 569-577.
35. Wiens D, Rourke JP, Casper BB, Rickart EA, LaPine TR, Peterson J. 1983. Channing: A nonflying mammal pollination of Southern African Proteas. *Annals of the Missouri Botanical Garden* 70(1): 1-31.
36. Fleming PA, Nicolson SW. 2013. Arthropod fauna of mammal-pollinated Proteahumiflora: ants as an attractant for insectivore pollinators? *African Entomology* 11(1): 9-14.
37. Fleming T, Nicholson S. 2013. Who is pollinating prhumiflora https://web.archive.org/web/20130219070835/ http://protea.worldonline.co.za/p52prhumi.htm.
38. Goldingay RL, Carthew SM, Whelan RJ. 1991. The importance of non-flying mammals in pollination. *Oikos* 61(1): 79-87. doi:10.2307/3545409. JSTOR 3545409.
39. Sühs RB, Somavilla A, Putzke J, Köhler A. 2009. Pollen vector wasps (Hymenoptera, Vespidae) of *Schinus terebinthifolius* Raddi (Anacardiaceae). *Brazilian Journal of Biosciences* 7(2): 138-143.
40. Cronk JK, Fennessy MS. 2001. *Wetland Plants: Biology and Ecology*. Boca Raton, Fla.: Lewis Publishers. pp 166. ISBN 978-1-56670-372-7.
41. Glover BJ. 2007. *Understanding Flowers and Flowering: An Integrated Approach*. Oxford University Press. p. 127. ISBN 978-0-19-856596-3.
42. New Living Science: Biology for Class 9. *Ratna Sagar*. pp 56-61. ISBN 978-81-8332-565-3.
43. Culley TM, Klooster MR. 2007. The cleistogamous breeding system: a review of its frequency, evolution, and ecology in angiosperms. *The Botanical Review* 73: 1-30. doi:10.1663/0006-8101(2007)73[1:TCBSAR]2.0.CO;2.
44. Baskin CC, Baskin JM. 2001. *Seeds: Ecology, Biogeography, and Evolution of Dormancy and Germination*. Elsevier. pp 215. ISBN 978-0-12-080263-0.
45. Igic B, Kohn JR. 2006. The distribution of plant mating systems: study bias against obligately outcrossing species. *Evolution* 60(5): 1098-1103. doi:10.1554/05-383.1. PMID 16817548.
46. Goodwillie C, Kalisz S, Eckert CG. 2005. The evolutionary enigma of mixed mating systems in plants: Occurrence, theoretic.al explanations, and empirical evidence. *Annu. Rev. Ecol. Evol. Syst*. 36: 47-79. doi:10.1146/annurev.ecolsys.36.091704. 175539
47. W SA. 2012. *In Patiny, Sébastien* (ed.). Evolution of Plant-Pollinator Relationships. Cambridge, UK: Cambridge University Press. pp 45-67.
48. Cardinal S, Danforth BN. 2013. Bees diversified in the age of eudicots. *Proceedings of the Royal Society* 280(1755): 20122686. doi:10.1098/rspb.2012.2686. PMC 3574388. PMID 23363629.
49. Steiner KE, Whitehead VB. 1990. Pollinator adaptation to oil-secreting flowers—Rediviva and Diascia. Evolution. 44 (6):1701-1707. doi:10.2307/2409348. Jstor 2409348. PMID 28564320.
50. Shao ZY, Mao HX, Fu WJ, Ono M, Wang DS, Bonizzoni M, Zhang YP. 2004. *Genetic Structure of Asian Populations of Bombusignitus* (Hymenoptera: Apidae). *Journal of Heredity* 95(1): 46-52. doi:10.1093/jhered/esh008. PMID 14757729.
51. Kuehn FC. 2015. Farming for native bees. World Wide Web electronic publication. Retrieved from. (Accessed: September 22, 2015).
52. Adamson NL. 2015. an assessment of non-apis bees as fruit and vegetable crop pollinators in Southwest Virginia. Diss. 2011.
53. Anonymous. 2006. *BioScience* 56(4): 315-317.
54. US Forest Department: Pollinator Factsheet (PDF). Retrieved 2014-04-18.
55. Biesmeijer JC, Roberts SPM, Reemer M, Ohlemuller R, Edwards M, Peeters T. 2006. Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science* 313(5785): 351-354.
56. Cox-Foster DL, Conlan S, Holmes EC, Palacios G, Evans JD, Moran NA. 2007. A metagenomic survey of microbes in honey bee colony collapse disorder. *Science* 318(5848): 283-287. doi:10.1126/science.1146498. PMID 17823314.
57. Woteki C. 2013. The road to pollinator health. *Science* 341(6147): 695. doi:10.1126/science.1244271. PMID 23950499.
58. EFSA Press Release: EFSA identifies risks to bees from neonicotinoids. Efsa.europa.eu. 2013-01-16. Retrieved 2014-04-18.

59. ISCA Technologies: A Leader of Innovative Pest Management Tools and Solutions". Iscatech.com. Archived from the original on 2014-04-10. Retrieved 2014-04-18.
60. Neuschulz EL, Mueller T, Schleuning M, Böhning-Gaese K. 2016. Pollination and seed dispersal are the most threatened processes of plant regeneration. *Scientific Reports* 6(1): 29839. doi:10.1038/srep29839. PMC 4951728. PMID 27435026.
61. David WR.2001. Ups and Downs in Pollinator Populations: When is there a Decline?
62. Carvalho CS, Galetti M, Colevatti RG, Jordano P. 2016. Defaunation leads to microevolutionary changes in a tropical palm. *Scientific Reports* 6: 31957. doi:10.1038/srep31957. PMC 4989191. PMID 27535709.
63. Connolly CN. 2013. The risk of insecticides to pollinating insects. *Communicative and Integrative Biology* 6(5): e25074. doi:10.4161/cib.25074. PMC 3829947. PMID 24265849.
64. Alam S, Chatterjee S, Paul A. 2022. Analysis of plant-based registered GI products of West Bengal. *Research Journal of Agricultural Sciences* 13(04): 1051-1054.
65. Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. 2010. Global pollinator declines: trends, impacts and drivers. *Trends in Ecology and Evolution* 25(6): 345-353.
66. CiteSeerX 10.1.1.693.292. doi:10.1016/j.tree.2010.01.007. PMID 20188434.
67. Fairbrother A, Purdy J, Anderson T, Fell R. 2014. Risks of neonicotinoid insecticides to honeybees. *Environmental Toxicology and Chemistry* 33(4): 719-731. doi:10.1002/etc.2527. PMC 4312970. PMID 24692231.
68. Humpden NN, Nathan GN. 2010. Effects of plant structure on butterfly diversity in Mt. Marsabit Forest – northern Kenya. *African Journal of Ecology* 48(2): 304-312. doi:10.1111/j.1365-2028.2009.01151.x.
69. Tylianakis JM. 2013. The global plight of pollinators. *Science* 339(6127): 1532-1533.
70. Sluijs JP, Vaage NS. 2016. Pollinators and global food security: the need for holistic global stewardship. *Food Ethics* 1(1): 75-91. doi:10.1007/s41055-016-0003-z.
71. Frankie GW, Baker HG, Opler PA. 1974. Comparative phenological studies of the trees in tropical wet and dry forests in the lowlands of Costa Rica. *Journal of Ecology* 62(3): 881-919.
72. Howlett BG, Butler RC, Nelson WR, Donovan BJ. 2013. Impact of climate change on crop pollinator activity in New Zealand. *The Weta, News Bulletin of The Entomological Society of New Zealand* 46: 1-52.
73. Free JB. 1970. *Insect Pollination of Crops*. Academic Press, London.
74. Kevan PG, Ambrose JD, Kemp JR. 1991. Pollination is an understory vine, Smilax rotundifolia, a threatened plant of the Carolinian forest, Canada. *Canadian Journal of Botany* 69: 2555-2559.
75. Abrol DP. 1993. Insect pollination and crop production in Jammu and Kashmir. *Current Science* 65(3): 265-269.
76. Endress PK. 1994. *Diversity and Evolutionary Biology of Tropical Flowers*. Cambridge University Press.
77. Kevan PG. 1999. Pollinators as bioindicators of the state of the environment: species, activity and diversity. *Agriculture, Ecosystems and Environment* 74: 373-393.
78. Buchmann SL, Nabhan GP. 1996. *The Forgotten Pollinators*. Island Press: Washington, DC.
79. Bustamante E, Búrquez A. 2008. Effects of plant size and weather on the flowering phenology of the organ pipe cactus (Stenocereusthurberi). *Annals of Botany* 102(7): 1019-1030.
80. Kearns CA, Inouye DW. 1993. *Techniques for Pollination Biologists*. University Press of Colorado, Colorado, USA.
81. Corbet SA. 1995. Insects, plants, plants and succession: advantages of long-term set-aside. *Agriculture, Ecosystem and Environment* 53: 201-217.
82. Hilton-Taylor C. 2000. *IUCN Red List of Threatened Species*. IUCN, Gland, Switzerland and Cambridge, UK.
83. Allen-Wardell G, Bernhardt P, Bitner R, Burquez A, Buchmann S, Cane J, Cox PA, Dalton V, Feinsinger P, Ingram M, Inouye D, Jones CE, Kennedy K, Kevan, P, Koopowitz H, Medellin R, Medellin-Morales S, Nabhan GP. 1998. The potential consequences of pollinator declines on the conservation of biodiversity and stability of food crop yields. *Conservation Biology* 12: 8-17.