

**REPRODUCTIVE ECOLOGY OF *PRUNUS CERASOIDES* D.
DON IN TROPICAL AND TEMPERATE FOREST CONDITIONS**

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY**

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**REPRODUCTIVE ECOLOGY OF PRUNUS CERASOIDES D. DON IN
TROPICAL AND TEMPERATE FOREST CONDITIONS**

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in Forestry of Mizoram University, Aizawl.**



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CERTIFICATE

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List of abbreviations and symbols

Acronym/symbol	Full form/meaning
°C	Degree Celsius
%	Percentage
<, >	Less and greater than
'	Minutes
"	Seconds
µg	Microgram
&	And
AM	Ante Meridiem
cm	Centimetre
et al.	Co-workers
FCR	Fluorochromatic reaction
E	East
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
GA ₃	Gibberellic Acid
g/l	Gram per litre
hrs	hours
g	gram
IAA	Indole-3-Acetic Acid
IKI	Iodine Potassium Iodide
P/O	Pollen-ovule ratio
IBA	Indole-3-Butyric Acid
T _{max}	Maximum temperature
K	Kinetin
min	Minute
mg	Milligram
mg L ⁻¹	Milligram per litre
N	North
e.g.	For example
PAR	Photosynthetically active radiation
pH	Potential of hydrogen
PM	Post Meridiem
ppm	parts per million
SEM	Scanning Electron Microscopy
Max.	Maximum
Min.	Minimum
mm	Millimetre
IUCN	International Union for Conservation of Nature and Natural Resources

a.m.s.l.	Above mean sea level
spp.	Species
SR	Stigma receptivity
A	Anthesis
H	Humidity
GLM	Generalized Linear Models
N	North
UK	Uttarakhand
MZ	Mizoram
T	Time
µm	Micro metre
NTFPs	Non timber forest products
m ²	Metre square
TTC	2,3,5-Triphenyltetrazolium chloride
SD	Standard deviation
ρ	Correlation coefficient
IPCC	Intergovernmental Panel on Climate Change
Nov	November
Dec	December
Oct	October
Feb	February
Mar	March
Jan	January
ICAR	Indian Council of Agricultural Research
Apr	April
Dist.	Distilled
CO ₂	Carbon dioxide
AD	Anther Dehiscence
T	Temperature
ANOVA	Analysis of Variance
H ₂ O ₂	Hydrogen peroxide
GIS	Geographic Information System
IBM	International Business Machines
SPSS	Statistical Package for the Social Sciences
±	Plus or minus

CHAPTER 1

Introduction

The *Prunus* genus, generally referred to as stone fruits, comprises approximately 430 species (Burgos *et al.*, 2007; Vicente *et al.*, 2011). Vitanova (1940) categorization divides it into five subgenera: *Amygdalus* (almonds and peaches), *Prunus* (plums and apricots), *Cerasus* (sweet and sour cherries), *Laurocerasus* (bay cherries), and *Padus* (bird cherries) (Gharaghani *et al.*, 2017). Commercially important fruit species such as peach and nectarine (*P. persica* L.), plum (*P. domestica* L., *P. salicina* Lindl., *P. cerasifera* Ehrh.), cherry (*P. avium* L., *P. cerasus* L.), apricot (*P. armeniaca* L.), and almond (*P. dulcis* (Miller) D. A. Webb.) have their origins in Europe, western and central Asia, and China. These species have naturally spread across temperate regions (Burgos *et al.*, 2007; Faust *et al.*, 2011; Vicente *et al.*, 2011). India is home to 36 identified species of *Prunus*, with 18 of them being cultivated for diverse uses (Pandey *et al.*, 2008). Many wild species, cultivars, and genotypes of stone fruits represent significant genetic resources, contributing to considerable genetic diversity. This diversity is crucial for breeding new varieties or rootstocks to meet market demands and growers' needs (Gharaghani *et al.*, 2017; Martínez-Gómez *et al.*, 2003).

Among these several species, *P. cerasoides* is a deciduous tree that comes under the Rosaceae family, which stands out for its distinct characteristics and ecological importance. Commonly known as the Himalayan wild cherry in English, it is also called Padmaka in Sanskrit and Tlaizawng in Mizo. It is naturally found in the deciduous, evergreen, and pine forests in the mountains of the Himalayas, Yunnan, Myanmar, northern Thailand and northern Indo-China. This species is located in the subtropical and temperate parts of the Himalayas, and it represents the diverse range of plant and animal life as well as the cultural traditions linked to the *Prunus* genus. In India, it is indigenous to the temperate Himalayan region extending from Himachal Pradesh in North-central India to Northeast regions. In the NE region it is

mainly found in Sikkim, Assam, Khasi hills, Manipur, and Mizoram (Pandey *et al.* 2008).

P. cerasoides is one of the 31 multipurpose tree species of the Himalayan region (Samant *et al.*, 2007) growing in scattered form on sloping ground between 1,200 and 2,400 m and attaining 10–11 m height on all types of rocks and soil (Troup, 1921). *P. cerasoides* has been identified as one of the promising ‘framework tree species for the restoration of evergreen forest in Thailand (Pakkad *et al.*, 2004). The tree is mainly insect-pollinated, and various insects, including bees and butterflies, play a role in pollinating their flowers. Bees, in particular, are important pollinators. Self-incompatibility of *P. cerasoides* exhibits meaning that a tree cannot pollinate its own flowers. Cross-pollination between different conspecific trees is required for the production of fruits. Fruit development of this tree after successful pollination, the flowers develop into fruits. The fruits are typically small and round and turn from red to black when ripened. Also, the seeds of *P. cerasoides* are typically dispersed by birds and animals that consume the fruits. This helps in the natural spread of the plant species.

Understanding the ecology of *P. cerasoides* helps to highlight its role in the natural environment and underscores the need for conservation measures to ensure the continued health of this species and the ecosystem it inhabits. The presence of *P. cerasoides* in the forest ecosystem contributes to biodiversity by providing food and habitat for various organisms. It often grows alongside other plant species, enhancing the overall ecological balance. Its fruits are also an essential food source for various wildlife species, including birds, such as bulbuls and thrushes, as well as small mammals. These animals play an important role in dispersing the seeds, contributing to the species propagation. Due to its deciduous nature, it produces vibrant white to pink flowers in late winter or early spring. *P. cerasoides*, like many other species, faces threat from habitat loss due to deforestation and land use changes. Conservation efforts aim to protect and preserve these trees and their ecosystems. The success of their reproductive cycle is influenced by the timing, intensity, and duration of flowering in plants, which in turn can have an adverse impact on the population of

pollinators, animals and frugivores that rely on the plant. Studies on mating systems, pollen biology, and pollinator availability are important as it is highly valuable for species to be used in restoration programmes. It employs various crucial mechanisms in its reproductive ecology to guarantee effective pollination and reproduction. Typically flowering in the spring, *P. cerasoides* produces clusters of pink to white blossoms timed to coincide with the arrival of pollinators.

Animals that consume the fruits play a vital role in the dispersal of seeds. They consume the fruits, and the seeds traverse their digestive systems. When animals defecate the seeds in various areas, it can result in the establishment of new trees, thereby facilitating the expansion of the species. In addition, certain seeds have the ability to fall to the ground and enter a state of dormancy before they start to grow. This adaptation enables the species to survive and adapt to changes in environmental conditions. *P. cerasoides* wood is renowned for its mild hardness, strength, durability, and fragrant characteristics, which are essential for many local ceremonies. The heartwood, known for its excellent seasoning properties, is sometimes employed in the creation of decorative furniture and for construction applications. Furthermore, the wood and root suckers are superb for crafting walking sticks and umbrella handles. *P. cerasoides*, in conjunction with *Prunus nepalensis*, is frequently used as a source of fuel and fodder in Sikkim (Chettri and Sharma, 2009).

This genus is highly valued for its decorative appeal, attributed to its vivid blossoms, and is regarded as sacred in Hindu customs, where the flowers are presented as offerings to deities. The plant is grown for its visual attractiveness and the commercial value of its fruits in the hilly regions of Khasi, Garo, and Jowai. Additionally, it is used as hedgerows. The fruit is consumable, and the flesh is utilised in the production of cherry brandy. The blooming period of this particular species (October–December) is of utmost importance as it offers bees a source of food during a time when other options are scarce. This makes it highly advantageous for beekeeping in the Himalayas. The species is widely acknowledged for its ethnomedicinal use throughout the region. The bark has been documented to possess therapeutic properties for healing

wounds, swelling, dyspepsia, foot and mouth illnesses, and bone fractures (Arora and Mahajan, 2019).

The fruit is utilised for its astringent properties and as a digestive aid, while the seed oil functions as an emollient and is deemed beneficial for various ailments, including stomach troubles, seminal weakness, leprosy, hallucinations, leucoderma, erysipelas, burnings, vomiting, asthma, hiccough, sprains, wounds, ulcers, skin discoloration, diarrhoea, and cardiac debility (Pullaiah, 2006). The seed kernels are additionally employed for the treatment of renal calculi (Chatterjee and Pakrashi, 1991). Nevertheless, the plant harbours cyanogenic glycosides such as amygdalin and prunasin, which have the potential to liberate cyanide upon consumption. When consumed in tiny amounts, these substances have the ability to enhance breathing, optimise digestion, and foster a feeling of overall wellness. When used in higher amounts, these substances can lead to severe health problems such as difficulty breathing, muscle weakness, heightened arousal, enlarged pupils, muscle contractions, seizures, unconsciousness, and failure of the respiratory system (Bown, 1995).

The leaves of *P. cerasoides* contain a variety of chemical compounds, including flavonoids, alkaloids, terpenoids, phenolics, tannins, saponins, steroids, and glycosides. The phenolic chemicals, specifically, have the ability to act as natural antioxidants (Joseph *et al.*, 2016). The gum produced by the plant, which consists of arabinose and galactose, exhibits antioxidant qualities when tested in a laboratory setting and has the potential to be utilised in the pharmaceutical industry. This gum is also recognised for its anti-abortion, analgesic, carminative, contraceptive, expectorant, antispasmodic, febrifuge, and tonic properties (Dhar *et al.*, 1968; Blando *et al.*, 2004). In addition, the bark's aqueous extracts have been found to possess antibacterial and anti-biofilm properties against disease-causing microorganisms (Arora and Mahajan, 2019).

Comprehending the reproductive ecology of untamed tree species is essential, yet the availability of data is frequently restricted (Chan *et al.*, 2011). A study of reproductive

phenology is crucial for comprehending breeding systems, management practices, and the availability of pollination for valuable, rare, and endangered species. Understanding the flowering biology of a population is crucial for preserving wild species that often inhabit specialised or limited environments. This knowledge allows us to assess the population's potential to reproduce and the movement of genes within it (Marten and Quesada, 2001; Lee *et al.*, 2006). The reproductive cycles of plants can have a substantial impact on pollinators, animals, and frugivores that rely on them. This impact is determined by factors such as the timing, intensity, and duration of blooming (Newstrom *et al.*, 1994). Investigating pollen biology, the availability of pollinators, and mating systems is crucial since it directly impacts the genetic contributions to future generations within species, therefore offering vital insights for restoration programmes. However, the wild potential resources of *P. cerasoides* have reduced drastically at an alarming rate, which can be attributable to the low seed germination capacity and its continuous use for its aesthetic values for beautifying landscapes through various projects (Tewari and Tewari 2016).

Susceptibility of germplasm base of *Prunus* to environmental stress, hazards, climate change/global warming mainly due to scattered and rare occurrence of species, lower rate of seed production, disease resurgence, and insect-pest or incidence, low regeneration, competition with other dominating species, overutilization for commercial purposes, and urbanization load has reached an alarming stage, and currently this vast diversity is endangered (Russell, 2003). The wild resources of *P. cerasoides* have dramatically declined due to its low seed germination and low seed set (Tewari and Tewari, 2016). Currently, *P. cerasoides* is classified as “data deficient” in the IUCN Red List of Threatened Species (Rhodes *et al.* 2016). The species needs to be better studied and prioritized as a conservation target. Previous conservation studies of *P. cerasoides* mainly focused on its propagation (Duan, 2003) and population diversity (Duan and Fan, 2004).

1.1 General morphology and distribution of *P. cerasoides*

P. cerasoides is a large or medium-sized deciduous tree. The leaves are ovate and elliptic-lanceolate, membranous, blade 7.5-12.5 cm, dark glossy, nearly glabrous, margin sharply serrate, with one or more conspicuous glands on the petiole. The inflorescences of *P. cerasoides* arise from lateral buds and are typically arranged in clusters, either fascicled or in umbels, usually containing three glabrous (smooth and hairless) flowers. Heart Wood is reddish brown, closely grained, moderately strong; it is durable, and seasons well. It is resistant to fungus and insect attack and works to a good finish, whereas sapwood is whitish and lustrous. Bark is reddish brown, smooth, peeling off in thin horizontal strips. Stipules long, glandular, 3-5 parted and fringed. Flowers are pinkish white or crimson, having a diameter of 2.5 cm in umbellate fascicles and peduncles. The tree blooms in the month of October and the fruit ripens from April to May. The fruits are green at the early stage and turn red when they become mature.

The distribution range of *P. cerasoides* extends in the Himalayas from Himachal Pradesh in north-central India to Nepal, Myanmar, Thailand, Bhutan, and West China. In NE region, it is mainly found Sikkim, Assam, Khasi hills, Manipur. and Mizoram. *P. cerasoides* is one of the most economically, ecologically and ethno-medicinally important plant species, which is widely used for various purposes. It can be considered as a potential multi-purpose tree species that can be suitably used for alleviation of the socio-economic status and human health improvement, and it is still considered as an under-utilized potential tree species in many parts of the world.

1.2 *P. cerasoides* as a multiple use tree

P. cerasoides has a wide range of uses. The parts used are stem, bark, fruits, heartwood, and seeds. The plant is regarded as sacred and is conserved for religious purposes. The plant is preserved for religious purposes and used by the local residents in rituals. The wood of *P. cerasoides* trees is moderately strong, hard, aromatic, and durable, and is used by the local inhabitants in several rituals. The fruits are seldom

eaten raw due to their acidic and astringent taste, though the ripe fruits are edible. Nevertheless, it is often cooked and used to make cherry brandy and sauces (Tanaka and Nakao, 1976).

Gum exuding from branches and trunks can be used as an alternative for gum tragacanth. The heartwood, which seasons well, is rarely used for making decorative furniture and building purposes. The root suckers, branches, and wood make exceptional umbrella crooks and walking sticks. Young branches are used as toothbrushes (Singh and Nautiyal, 1991) and leaves as fodder. A dye can be obtained from the leaves and fruit. The bark is a resource of tannins (Grae, 1974). The seeds are used as beads in necklaces and rosaries (Polunin and Stainton, 1984). The tree is mainly used as rootstock for the cultivation of cherries. Flowers provide a rich source of pollen and nectar for bees, so the plant has enormous apicultural significance. All four species of *Apis* present in India namely *Apis cerana indica*, *Apis florea*, *Apis mellifera* and *Apis dorsata* visit the flowers of *P. cerasoides* for their rich nectar and pollen (Gaur and Nanwani, 1989; Tiwari *et al.*, 2009; Awasthi, 2015). The tree has a wide range of ecological and economic importance, including its role in reproductive ecology.

1. 3 Reproductive ecology

Studying plant breeding systems, interactions between pollinators and plants, seed germination, floral characteristics, and much more is the focus of plant reproductive ecology (Molano-Flores and Cohen, 2024). Reproduction is an essential process in the life cycle of organisms, as it guarantees the continuation of their existence as a unique species. The innate biology of creatures and the "interactive" ecological realm in which they develop and thrive both have a significant impact on the process's effectiveness. Due to its influence on nearly every stage of reproduction, the second factor becomes extremely significant for plants. The primary reason for this is that plants are stationary, meaning that any characteristic of their complex growing environment may have the ability to limit the reproductive success of those plants (Shivanna and Tandon, 2014).

Reproductive ecology is a specialised area within the fields of evolutionary biology and ecology that investigates how biological and environmental factors interact to affect the process of reproduction in plants and animals. The primary objective of reproductive ecology is to comprehend the mechanisms and consequences of reproduction, encompassing the development of mating systems, timing of reproduction, life cycle strategies, sexual selection, and reproductive failure. It involves the study of all aspects of reproductive events and their impact on the biological and physical features of the environment. Studying the reproductive ecology in both temperate and tropical forests is crucial because these habitats have different environmental variables that lead to different reproductive strategies.

The importance of reproductive ecology rests in understanding the reproductive processes and outcomes, as well as informing conservation and wildlife management efforts. Gaining insight into these processes can yield vital data to tackle present difficulties, a significant number of which are a result of human actions such as habitat degradation, excessive exploitation, and dramatic alterations in land utilisation. These factors have resulted in a decrease in the populations of numerous plant species and their pollinators. By examining the reproductive strategies of plants, it is feasible to evaluate their capacity for survival and implement steps to preserve them (Bernardello *et al.*, 2001). It is crucial to comprehend the timing of flowering and seed production, the mechanisms of seed dispersal and germination, and the ecological factors that influence these natural phenomena. Thus, ecological approach to studying the reproductive biology of plants provides valuable insights into the dynamics of populations and communities.

Scientists employed reproductive tactics by a species at several levels of organisation, ranging from individual plants to the species' whole geographical range. Self-incompatibility may be the one of cause of low seed or fruit set in a species. Apart from that, an alternative explanation for limited fruit or seed set could be asynchronous flowering, the existence of several co-flowering species, inadequate flowering to draw pollinators, inadequate pollination, heterospecific pollen transfer, lack of pollinators, insufficient availability of compatible mates, or trade-offs resulting

from conflicts in resource allocation between various functions (Larson and Barrett, 2000; Morales and Traveset, 2008). A comprehensive comprehension of a species' reproductive ecology is crucial for the efficient management, conservation, and sustainable utilisation of species. Insufficient knowledge about reproductive ecology will render conservation efforts futile. According to Kwak and Bekker (2006), species that have undergone successful restoration are usually well-researched, especially in terms of their reproductive ecology. Therefore, "elucidation of all aspects of reproductive events and their interactions with the biotic and abiotic components of the environment" is essentially what reproductive ecology studies entail (Shivanna and Tandon, 2014).

1.4 Reproductive phenology

Reproductive phenology describes the temporality of key events in the life cycle of organisms. It corresponds to a period when resource allocation is diverted towards reproduction at the expense of parental survival and growth. Variation in flowering phenology among members of a population is considered to affect their reproductive success and thus influence their fitness (Ratchke and Lacey, 1985; Fenner, 1998; van Schaik *et al.*, 1993; Chuine, 2010; Forrest and Miller-Rushing, 2010; Morellato *et al.*, 2010). Phenological patterns differ significantly across the species' geographic range, and the timing of plant phenological behaviour can impact ecological processes, such as the demographic patterns of species (Miller-Rushing and Inouye, 2009). The differences from previous study were detected in the duration, onset and magnitude of flowering in which reproductive success among individual plants within a population may be affected (Bawa, 1983; Gomez, 1993; Newstrom *et al.*, 1994; Munguia-Rosa *et al.*, 2011 a, b).

Differences in the timing of reproduction among species that live together decrease competition and support the preservation of a wide variety of species in ecosystems (Craine *et al.*, 2012b). The reproductive timing of species is not constant and can be influenced by climate variations (Anderson *et al.*, 2012). Day length, light quality, temperature, atmospheric CO₂ concentration, and dryness are factors that influence

the timing and length of flowering. Recent studies have demonstrated that the timing of reproduction in species is influenced by environmental factors as well as life history, photosynthetic pathway, and phylogeny (Davies *et al.*, 2013; Du *et al.*, 2015; Cortés-Flores *et al.*, 2017; Munson and Long, 2017). Factors such as water stress, humidity, temperature, and the time of nutrition availability can directly impact phenology (Wright, 1991). In temperate locations, the temperature experiences significant seasonal changes, and natural activities like flowering follow a clear seasonal cycle, such as blooming in spring. Meteorological conditions and the timing of fruiting and flowering are clearly associated in this context.

Tropical systems have a variety of flowering patterns and experience consistent warmth and rainfall throughout the year, which encourages flowering (Newstrom *et al.*, 1994; Bawa *et al.*, 2003). Climate change in temperate habitats affects the timing of plant life cycle events, leading to different phenological shifts among species (Borchert, 2004). In tropical ecosystems, climatic oscillations are less pronounced compared to temperate regions, resulting in less obvious plant responses to climate variations. Tropical tree communities display clear and significant seasonal patterns in blooming, fruiting, and leaf growth events when compared to other types of plants (van Schaik *et al.*, 1993; Singh and Kushwaha, 2006). Understanding flowering patterns requires analyzing extensive datasets collected over several years. The intensity of flowering can affect the selection of pollinators by influencing the timing of flowering, which in turn can impact the choice of pollinator species.

Pollinator visitation rates are determined by flower initiation (Augspurger, 1980, 1983; Kudo and Harder, 2005; Elzinga *et al.*, 2007; Collin and Shykoff, 2010; Internicola and Harder, 2011). Plants artificially induced to flower earlier or those naturally flowering later had lower pollination success and fruit set than normally flowering plants, suggesting that stabilizing selection on flowering time was responsible for the high synchrony and mass flowering pattern. Trees growing in continuous forests are more likely to have pollen deposited on their stigmas and are more likely to set fruits and produce more seeds per fruit than trees isolated in pastures (Rocha and Aguilar, 2001). Reproductive phenology determines the linkage between

radial growth, fruit production and climate. Seed and fruit production in trees are dependent upon various factors which includes acquisition and resources availability, climate, pollinators availability or storage endogenous dynamics (Kelly and Sork, 2002; Vergotti *et al.*, 2019). According to the resource-budget hypothesis, full seed crops cannot occur every year due to the high cost of production, climatic factors and stored reserves of trees seem to be largely species-specific and contingent on local conditions (Nussbaumer *et al.*, 2018).

1.5 Floral phenology, pollen transfer, and stigma receptivity

The most important aspects of floral biology are when flowers open (anthesis), when stigmas become receptive, and how long pollen is present inside a flower. These features influence a flower's lifetime and are related to its breeding and pollination processes. At the flower level, the key pheno-events encompass the timing of flower opening (anthesis), anther dehiscence, stigma receptiveness, pollination, and the longevity of the flower (Shivanna and Tandon, 2014). Some of the prominent floral functions that determine the effectiveness of advertisement to draw pollinators includes floral display (colour, shape, size, olfaction), their presentation in the plant (solitary or in an inflorescence; enantiomorphy), longevity, anthesis time, relative positions (herkogamy), and timing of maturation (dichogamy) of essential organs, presentation, and type of rewards (Waser and Price, 1981; Mitchell *et al.*, 2009). If more than half of a species' population is in bloom, it is deemed to be in blooming (Stiles, 1978).

Timing and duration and frequency are intricately connected. The frequency of flowering must therefore be taken into consideration in order to fully comprehend the timing and duration of flowering at the community level (Bawa *et al.*, 2003). Due to the sensitivity of the phenological patterns to climatic circumstances, frequent small variations in ambient temperature are expected to have an impact on the phenological patterns (Easterling *et al.*, 2000, Abu-Asab *et al.*, 2001). Many of these features are thought to be affected by pollinator selection, which is imposed on the plants (Parachnowitsch and Kessler, 2010). Temperature within the floral space provided by

its form can significantly affect pollinator visits (e.g., Rosaceae) and, consequently, reproductive success in temperate and polar environments (Kevan, 1989, Dyer *et al.*, 2006).

Similar to the magnitude of the display, the lifespan of flowers affects pollinator attraction and the number of foraging trips (Mathur and Mohan Ram, 1978; Shivanna and Tandon, 2014). It usually refers to the amount of time that flowers can stay fresh in the field (Primack, 1985); however, according to Shivanna and Tandon (2014), it specifically defines it more accurately as the amount of time that flowers can disseminate or receive pollen. In pollinator-limited situations, long-lived blooms can more than offset low pollinator visitation rates to ensure adequate receiving and encourage pollen export (Arroyo *et al.*, 2017). In various plant-pollinator systems, many pollen vectors visit flowers, but not all visitors function as effective pollinators. Moreover, the efficiency of those that do act as pollinators can differ significantly (Stebbins, 1970; Herrera 1987, 1989). Most often, successful pollen transfer requires contact between a flower's reproductive organs and a visitor in such a way that pollen is picked up on the visitor's body and dropped on the stigmatic surface of the host plant (Faegri and van der Pijl, 1979).

Additionally, the duration of pollen viability following anther dehiscence is critical to successful pollination (Stone *et al.*, 1995), especially for out-breeders, as it dictates the likelihood of interspecies out-crossing. Regarding Indian hardwoods, there is a dearth of information regarding this matter, with the exception of a few sparse reports (Khurana and Khosla, 1979; Chauhan and Katiyar, 1996). The ability of pollen grains to survive in the environment and yet have the potential to germinate and form a developing pollen tube on a stigma or pistil that is receptive is known as pollen viability (Edlund *et al.*, 2004). The pollen tube serves as a conduit for the transportation of sperm cells to the ovule, so the process of seed and fruit formation commences following fertilisation. Pollen viability, longevity, and pollen tube performance are crucial factors for the natural propagation of plant species, as well as for breeders who require the collection, storage, and global transportation of pollen to

create new hybrids. Additionally, farmers depend on pollen performance to ensure high yields of seed and fruit crops.

According to the IPCC, the majority of agricultural regions would see heightened environmental fluctuations in the next few decades, such as significant changes in temperature, rainfall, wind speed, and direction (IPCC, 2014). The swift environmental changes will affect the ability of pollen to survive, its lifespan, its effectiveness, and its movement between organisms for both species that are pollinated by wind and animals. It is crucial to comprehend the influence of climate change on the timing and amount of pollen generation, as well as on the viability, duration, and performance of pollen (Mercuri *et al.*, 2016).

Pollinator movement across plants is also necessary for species that are obligatory outcrosses. Therefore, the effectiveness of this procedure depends on both the flower's morphology and the visitor's behaviour (Muchhala, 2003). A theory proposed by Robertson (1895) in the 19th century suggests that competition for pollination among flowering plants may play a significant role in the evolution of traits related to pollination, such as preference for specific habitats, timing of flowering, floral shape, and the types of pollinators they attract. However, later on, Levin and Anderson (1970), discussed how sharing pollinators could also lead to competition. It is important to have a good understanding of the specific mechanisms and the extent of their impact, as the outcomes of interactions between plants through pollination are heavily influenced by the specific ecological and evolutionary mechanisms involved (Rathcke, 1983) and (Galen and Gregory, 1989).

Various meteorological conditions, such as temperature, humidity, precipitation, and sun radiation, can have an impact on the commencement of flowering (Requile *et al.*, 2021). The density and diversity of pollinators, their visit frequency, and the quantity and quality of pollen reaching the stigma are crucial parameters that influence the effectiveness of pollination in plant species that rely on animal pollinators (Kremen *et al.*, 2007). Pollen dispersal, deposition, germination on the stigma, and subsequent pollen tube elongation are discrete phases in the process of flower pollination and

fertilisation. The reproductive success of plants is affected by the way their flowers are arranged, how often they bloom each day, and the number of visits by pollinators that result in successful pollination and fertilisation (Thakur *et al.*, 2018).

Tropical trees usually require animal pollination to generate seeds since they are self-incompatible (Bawa 1974, 1990). Consequently, the reproductive output of a tree species may be significantly impacted by disturbances that hinder pollen travel routes. Herkogamy and dichogamy may decline if outcrossing is unsuccessful, self-incompatibility (SI) in many plants is not always present (Nasrallah and Nasrallah, 2014), and plants may interact mutualistically with many pollinator species (Johnson and Steiner, 2000). The pattern of mating is strongly influenced by the synchronicity of flowering among the plants in a population. Out-of-phase blooming can frequently be attributed to the genetic diversity that exists within a population (Bullock and Bawa, 1981; Opler *et al.*, 1980). A high pollen output leads to high fruit/seed setting and proper pollen reception by the stigma, which impacts the viability and abundance of the plant population. The success of plant mating depends on various factors that can influence *in vitro* pollen germination, including the species, culture media, temperature, incubation period, flower development stage, and storage conditions (Stanley and Linskens, 1974).

The most recent complete evaluation of pollen viability, conducted over twenty years ago, examined techniques for determining viability and examined the internal and external elements that affect this crucial aspect for successful reproduction (Dafni and Firmage, 2000). To achieve successful reproduction, plants modify their reproductive system to accommodate pollination success and fertilization. To fertilize and develop into a seed or fruit, the capability of pollen to mature is required. Inside the anther, the pollen grains develop, and they begin to dehydrate in a metabolically inactive state during anther maturity. They act as autonomous functional units and are exposed to the ambient environment once the pollen is released from the anther. The receptive stigmas receive this pollen through various pollinating vectors within a certain period and this leads to pollination. While breeding a plant species, it is important to know the correct method for measuring the pollen viability (Dafni and Firmage, 2000).

Pollen viability and *in vitro* pollen germination are directly correlated with the production of fruit and seed. Studies have shown that in most flowering plants, the process of pollen grain germination occurs after the ovule structure and embryo sac have fully matured. As a result, fertilisation usually takes place several days or months after pollination (Chen and Fang, 2016). Various environmental factors can affect the time between when a flower opens and when its stigma is ready to receive pollen. These elements can potentially decrease the ability of pollen to fertilise and cause the stigma to become dry when temperatures are high. During the reproductive process, plants face many environmental constraints. Plants modify their reproductive systems to promote pollination and fertilisation, therefore ensuring effective reproduction. To get insight into sterility difficulties, hybridization programmes, fruit breeding initiatives, and evolutionary ecology, researchers conduct artificial pollination and breeding studies to evaluate pollen viability (Bandeira *et al.*, 2021).

The timing and duration of stigma receptivity play a critical role in separating the male and female reproductive stages, significantly influencing the adhesion, hydration, and germination of pollen. The extent of stigma acceptance determines the period during which successful pollination can occur, thereby impacting fruit production. Stigma receptivity varies among species and is influenced by environmental conditions (Hedhly *et al.*, 2003). Stigma receptivity refers to the ability of a stigma to support the growth of viable pollen from compatible sources (Yi *et al.*, 2006). However, research on stigma receptivity has been limited to a few species (Shivanna, 2003), and its impact on the development of germinating pollen and pollen tubes remains unclear (Yi *et al.*, 2006). Viability assays are used to evaluate pollen germination on stigmas, providing insights into sterility issues, hybridization programs, fruit breeding, and evolutionary ecology (Gupta and Murty, 1985; Oberle and Watson, 1953; Stone *et al.*, 1995; Thomson *et al.*, 1994).

Pollen viability, which reflects the ability of a pollen grain to deliver sperm to the embryo sac after pollination, is a key factor in these assessments. However, evaluating pollen viability based on its function can be complex, time-consuming, and sometimes impractical (Heslop-Harrison *et al.*, 1984). The most reliable method is assessing the

pollen's capacity to facilitate fertilization and seed formation, though a successful seed set confirms viability, whereas the absence of seeds does not necessarily indicate non-viability. Research into pollination provides critical insights into the fertilization process in plants and highlights the importance of pollinators. Such knowledge can guide efforts to conserve pollinators while improving crop productivity. Identifying the optimal timing and conditions for fertilization is essential for advancing plant breeding. Additionally, understanding pollen characteristics and durability supports the effective preservation and transfer of pollen, which is crucial for breeding programs. *In vitro* studies of factors promoting pollen germination can further enhance plant breeding strategies.

1.6 Pollen production and mating success in plants

Pollen, as a microscopic grain discharged from the male part of a flower or male plant, contains male gametes crucial for fertilization and seed development. Its production is influenced by a complex interplay of biotic and abiotic factors essential for successful mating and fruit set in flowering plants. Annually, these plants release substantial amounts of pollens, heavily influenced by environmental conditions and flower density. Every year, an enormous number of pollens is released by flowering plant species. The environment in which the plant grows and the number of flowers, influences the production of pollen. The main determinants of pollen production are the anther's length and the size of the pollen grains (Pletsers *et al.*, 2015). Climate also influences the density of the flowers in the plant (Khanduri *et al.*, 2013). The altitude and the location in which the plants of the same species grow determines the difference in production of pollen. A plant's ability to function biologically is reflected in its pollen productivity. Typically, it is believed that the effectiveness of pollination is closely linked to the quantity of pollen produced (Regal, 1982; Whitehead, 1983).

Several factors, including the pollen grain count per anther, the number of anthers per flower, the number of flowers per inflorescence, the number of inflorescences per tree, and the size of the tree influence the pollen output of a tree. According to Fñ gri and Iversen (1964), the production of pollen is also influenced by the frequency of

flowering years. In woody species, pollen production varies significantly between different species and within the same species across different sites and years, reflecting the complex interplay of genetic predispositions and environmental influences (Teresa Gómez-Casero *et al.*, 2004; Khanduri, 2012; Barwise and Kumar, 2020). Environmental variables exert a profound effect on the regulation of pollen generation, leading to observable differences in pollen output across various locations and over different years. Location and altitude have a significant influence on pollen production in a species, which in turn affects the costs of reproduction and the fitness of individuals (Kyogoku, 2015). *Dactylis glomerata* is a prominent example, as its pollen output is affected by several climatic and geographic factors (Severova *et al.*, 2022). Pollen production is essential for the natural regeneration of plant communities in tropical forests and has a substantial impact on species reproduction (Schwartz *et al.*, 2017). Increased pollen production enhances the chances of the stigma obtaining an adequate amount of pollen, resulting in higher fruit and seed production. This, in turn, has an impact on the abundance of plants and their ability to sustain a population. (Khanduri *et al.*, 2015a).

Environmental conditions also have an impact on pollen production (Damialis *et al.*, 2011). Monitoring pollen yield from different species is crucial for assessing local and global environmental changes, as pollen production is affected by environmental fluctuations (Rogers *et al.*, 2006). The overall pollen output of a single plant is influenced by a complex interplay of genetic, physiological, and environmental factors. Climatic conditions, as highlighted by Scamoni (1955), play a crucial role in influencing pollen production in various deciduous forest trees, as well as species like spruce and pine. These factors dictate the timing of flower opening, the release of pollen from anthers, and the density of flowers, ultimately affecting the amount of pollen each plant produces (Stanley and Linskens, 1974).

In addition to climatic influences, pollen production in trees is affected by several specific parameters: the number of pollen grains per anther, the quantity of anthers per flower, the abundance of blooms per inflorescence, the number of inflorescences on the tree, and the overall size of the tree. These statistics are invaluable in

aerobiology, offering insights into how different species disperse pollen through the air. Moreover, they hold particular significance for the forestry industry, where seed production often hinges on effective pollen production and dispersal strategies (Campbell and Halma, 1993). The quantity of pollen generated by an individual plant and among a plant community is not constant; it fluctuates considerably depending on ecological conditions, particularly climate. As a result, the process of flowering and the production of pollen in a forest show significant variety. In addition, a tree that is completely exposed to its surroundings, such as one that grows in an open field, generates significantly higher amounts of pollen in comparison to a tree in a dense forest, even if the latter extends to the uppermost part of the forest canopy. Immature or inhibited trees release limited pollen as they are unable to reach the upper canopy. Erdtman (1954a), Hansen (1949), and Faegri (1956) have recognised the effects of size class, vigour, climate, site, and meteorological phenomena like sunshine, temperature, wind direction, velocity, and turbulence on pollen output per species (Potter and Rowely, 1960).

Pollen production in large quantities enhances the process of pollination, resulting in higher yields of fruits or seeds. This, in turn, has a direct effect on the plant's overall abundance, population sustainability, and the success of its reproductive system. Floral evolution and the morphological traits modify the actions of pollen vectors so as to enhance fertility and mating success (Harder and Barrett, 1996). Physiological characteristics counteract the ineffective dispersal of pollen by rejecting unsuitable male gametophytes or zygotes. This rejection process is supported by various studies (Jones, 1928; de Nettancourt, 1977; Marshall and Ellstrand, 1986; Seavey and Bawa, 1986; Barrett, 1988; Snow and Spira, 1991; Walsh and Charlesworth, 1992; Stephenson, 1981; Casper, 1988; Becerra and Lloyd, 1992; Montalvo, 1992). As a result, post-pollination processes ensure that the actual mating patterns differ from the initial pollination patterns. These processes refine the initial mating framework established during pollination, indicating that pollination sets the limit for the frequency and diversity of mating opportunities. Consequently, pollination plays a crucial role in shaping the evolution of mating systems, closely connecting the development of pollination and mating strategies. The majority of flowering plants

possess floral organs designed to attract the insects that pollinate them. Insect visitation and pollination are not fortuitous, but rather, they are recurrent processes. In order to identify gene flow and heterozygosity in the population, which affect genetic variability in tree populations, research on pollen grains and pollen production is essential for tree development programmes (Sharma and Khanduri, 2007).

The method of reproduction of a species can account for differences in pollen production (Smart *et al.*, 1979). Fryxell (1957) found that plants with high pollen production in their anthers were mainly cross-pollinated and self-incompatible, unlike pollen producers, which may be either self-pollinated or cross-pollinated. The generation of pollen has been examined in relation to several factors, such as the size of the species, its vigour, climate, place, and meteorological phenomena including temperature, wind direction, velocity, and turbulence. This review has been conducted by Erdtman (1943), Hansen (1949), Faegri and Iversen (1950), and Potter and Rowley (1960). The literature on pollen production in gymnosperms is limited. Erdtman (1943), Pohl (1937b), and Sarvas (1962) reported pollen production figures of 158×10^3 , 152×10^3 - 162×10^3 , and 151×10^3 - 164×10^3 pollen grains per strobilus, respectively, in *Pinus sylvestris*. Tormo *et al.*, reported figures of 20.9×10^9 - 32.3×10^9 pollen grains per tree in the same species.

Pollen production is significant for both fundamental studies and practical uses. There are many benefits to studying flowering patterns and doing pollen analysis at the tree level. It makes it possible for tree breeders to time crossbreeding precisely. By using particular testing and breeding techniques, foresters and silviculturists can use this information to increase the quality of wood. Natural selection and the evolution of plant life cycles are topics that ecologists and evolutionary biologists can explore. Pollen allergen release rates and the beginning of pollen seasons are predictable to aerobiologists. Therefore, in forestry and agriculture, pollen production estimation is essential for forecasting future yields and the size of fruit and seed crops (Allison, 1990; Westgate, 2003).

Assessing the quantity of pollen generated by particular species holds considerable importance for both public health and agriculture (Castiñeiras, *et al.*, 2019). Examining pollen production and viability offers valuable insights into future harvests. This analysis enables the development of prediction models months in advance (Ferrara *et al.*, 2007; Oteros *et al.*, 2014). By leveraging this data, the allocation of personnel and resources for agricultural harvesting and processing can be optimized, leading to improved scheduling of production processes and marketing strategies for products (Fernández-Rodríguez *et al.*, 2016; Orlandi *et al.*, 2017; Rojo and Pérez-Badia, 2015).

Numerous studies have explored pollen release concerning reproductive phenology status, genetic factors, and environmental conditions (Ishida and Hiura, 1998; Kouboris *et al.*, 2012; Rojo *et al.*, 2015). Climate change may impact weather-related elements, consequently influencing both the quantity and quality of generated pollen. Ultimately, this can affect the allergenic potential of pollen (Bonofiglio *et al.*, 2013). The quantity of pollen generated by a plant is determined by the structure of its floral organs and the methods it uses to disperse pollen (Cruden 2000; Friedman and Barrett 2009). While a plant's total pollen grain output is affected by various factors (Stanley and Linskens, 1974) and can vary from year to year (Rogers, 1993), it is important for commercially valuable plants to determine the exact amount of pollen produced by each plant. Estimating seed production is crucial as it is usually dependent on pollen production (Faegri and Iversen, 1989; Cour and Van Campo, 1980). It is widely accepted that the effectiveness of wind pollination reduces as the amount of pollen in the air decreases (Regal, 1982; Whitehead, 1983). The decrease in effectiveness may be attributed to substantial spatial separation between plants of the identical species, limited pollen generation by individual plants, and inefficient distribution of pollen. It is hypothesised that these conditions have a detrimental effect on both ovule fertilisation and seed production (Allison, 1990).

The quality of pollen provided during pollination is crucial in plants that depend on animal pollination, especially when there is a scarcity of pollinators (Timerman and Barrett, 2021). Pollen germination and pollen tube growth are contingent upon the

density of pollen grains on the stigma, which is referred to as pollen density dependence. While the stigma may receive a greater amount of pollen grains compared to the ovules that are available for fertilisation, it does not guarantee successful fertilisation and fruit development. Pollen limitation refers to the situation where pistils do not get enough pollen grains to fertilise all ovules, resulting in reduced seed and fruit production in different plant species (Harder and Johnson, 2008).

A basic understanding of floral structure, sexuality and phenology is a prerequisite for understanding the floral life cycle and a necessary background for any pollination study. Further, plant-pollinator interaction, pollen germination, stigma receptivity and mating systems must be analyzed critically on a species by species basis, as it reflects the basic criteria for breeding programmes and proper planning for gene conservation. Henceforth, looking into the scientific study gap on reproductive ecology, the multipurpose tree species of the present study is proposed to work out, generate annual data variability in reproductive phenology, pollen production and pollinators availability in two naturally occurring geographical sites of India. Tropical tree species that rely on animal pollinators may experience pollen scarcity, resulting in reduced fruit and seed production compared to their flower and ovule production (Khanduri *et al.*, 2015a).

Animal-facilitated pollination necessitates a substantial quantity of pollen to ensure effective pollination, especially for plants that rely on bees as their pollinators, as bees derive advantages from generating a significant volume of pollen. Therefore, the efficacy of pollination is heavily reliant on the rates at which pollen undergoes germination. Assessing the pollen output of a plant species would aid in evaluating its suitability as a food source for honeybees and wild bees. Categorising plants based on their pollen production would hold significance in both practical and intellectual contexts.

1.7 Pollinators availability

Pollinators hold a prominent position in both scientific literature and public awareness due to their crucial ecological and agricultural functions. They underpin a substantial portion of evolutionary innovation, making them some of the most critical ecological interactions within terrestrial ecosystems. Pollinators play a significant role in plant reproduction by facilitating seed production and shaping the evolutionary trajectories of plant-pollinator interaction. The interactions between plants and pollinators are not only essential for the majority of plant reproduction but also contribute significantly to the generation of diverse evolutionary paths in both the plants and the pollinators themselves (Ollerton, 2017). Without pollinators, numerous plant species would face challenges in achieving seed production and reproductive success. Additionally, the absence of plants providing pollen, nectar, and other rewards would lead to the decline of many animal populations, triggering cascading repercussions for other species within the ecosystem (Kaur and Kaleka, 2022).

On a global scale, there are more than 250,000 species of angiosperms, and 70% of them depend on insect pollinators for reproduction (Pannure, 2016). Nectar, primarily composed of a sugar solution, is regarded as the most vital floral incentive for animal pollinators (Nepi *et al.*, 2012). It functions as a crucial provider of nourishment and fuel, comprising an intricate blend of carbohydrates, amino acids, proteins, lipids, vitamins, antioxidants, alkaloids, organic acids, and inorganic compounds like minerals (Burkett, 1998). Insect-pollinated flowers typically produce a limited quantity of concentrated nectar, which attracts insects to visit several blooms. This behavior increases the frequency of floral visits and promotes outcrossing, as seen by McCallum *et al.*, 2013. According to Lemaitre *et al.* (2014), flowers that are pollinated by bats and hawk moths release a large amount of nectar at night, whereas flowers pollinated by bees, butterflies, and birds do so during the day.. Several insect species, such as bees, beetles, flies, thrips, and butterflies, rely on pollen as their primary source of nutrition (Cane, 2016).

Pollinators have a range of 3 to 12 kilometers for foraging, and their foraging rates vary as well (Anonymous, 2003). Bumblebees exhibit a foraging speed that is twice as high as that of honeybees. Additionally, the foraging rates of solitary bees differ dramatically based on their size (Goulson *et al.*, 2002). While foraging, honeybees, flies, bees, butterflies, and hawk moths exhibit rapid movement as they transition between flowers (Kulloli *et al.*, 2011). The altitude, temperature, light, wind, and rainfall have an impact on foraging behavior, flower visits, and pollination efficiency (Akhtar *et al.*, 2018). Hummingbirds demonstrate more efficacy as pollinators at higher elevations compared to bees, but moths exhibit higher effectiveness at middle and lower altitudes (Klomberg *et al.*, 2022). The temperature exerts a substantial influence on pollinators (Conrad *et al.*, 2017). Foraging is not observed below 8°C, is restricted between 8°C and 16°C, reaches its peak between 16°C and 32°C, and declines above 32°C, but a small amount of foraging may persist up to 42–48°C. The foraging behavior of bees is significantly influenced by changes in temperature (Abrol, 2010).

In recent years, there has been a significant increase in research on the ecology of pollination in forest trees, ornamental plants, and agricultural crops. However, there is comparatively limited research on the reproductive biology of medicinally significant plants in their natural environments (Kulloli and Sreekala, 2009). Due to climate change, there is significant stress regarding the population size of pollinators and their contribution to ecology (Hegland *et al.*, 2009; Potts *et al.*, 2010). Gathering information on all floral visitors of flowering plants in forestry and agriculture is crucial (Bronstein and Hossaert-McKey, 1995; Kearns *et al.*, 1998).

Pollination is an ancient ecological process that spans millions of years, providing benefits to both flowering plants and their pollinators. The mutualistic relationships between plants and their pollinators stand as captivating examples of co-evolutionary dynamics within the biosphere. Devoid of pollinators, numerous plant species would confront challenges in achieving seed production and reproductive success, while the absence of plants dispensing pollen, nectar, and other incentives would precipitate the decline of myriad animal populations, thereby triggering cascading repercussions for

other species within the ecosystem. The reciprocal influence of plants and their pollinators has exerted a notable effect on their respective growth trajectories, often culminating in divergence and occasionally fostering a unique symbiotic relationship (Kaur and Kaleka, 2022). Research has shown that insects visiting flowers show daily fluctuations, and there is evidence of various pollinator species visiting flowers at different times, suggesting temporal complementarity (Albrecht *et al.*, 2012). Two crucial criteria that affect the role of floral visitors as pollinators are the frequency of flower visits and the efficiency of pollination.

Pollination effectiveness refers to the degree to which a flower visitor successfully transports pollen to the stigma, resulting in successful seed formation each visit. Multiple research corroborates this viewpoint (Olsen, 1997; Schemske and Horvitz, 1984; Stebbins, 1970; Waser and Price, 1983; Ne'Eman *et al.*, 2010). Pollinator visitation frequency decreases as a result of several factors, including shifts in the geographic distribution of floral resources (Real *et al.*, 1982; Rathcke, 1983), a drop in pollinator abundance brought on by changes to the environment (Vinson *et al.*, 1993), resource availability (Schaal, 1980; Jennersten, 1988), or the competitive exclusion of pollinating species by inefficient pollinators from floral resources (Huryn, 1997). Recent scientific investigations have established a connection between diminished levels of pollination for both cultivated crops and indigenous flora within intensely managed agroecosystems and the concurrent decreases in the abundance and variety of pollinators.

Over the past few decades, there has been a global decline in the population of pollinators, including both wild and farmed species (Kevan, 1999). This gives rise to apprehensions regarding a possible pollination crisis (Kearns *et al.*, 1998). The decline of pollinators globally is a significant ecological crisis, as it has been observed even in protected areas (Hallmann *et al.*, 2017). Nevertheless, the worrisome trend of decreasing populations of pollinators, both in the wild and in domestic settings, has been observed globally in recent decades (Kevan, 1999)

Tropical trees exhibit a predominantly self-incompatible nature and rely on pollination facilitated by animals for the purpose of seed generation (Bawa 1974, 1990). Disruptions that influence the animal vectors responsible for pollen transmission can, therefore, have an impact on the reproductive success of tropical trees. The decline in pollinator abundance, changes in resource availability, the spatial distribution of floral resources, and competitive exclusion from floral resources by inefficient pollinating species are all factors that can disrupt pollination processes (Huryn, 1997; Ghazoul *et al.*, 1998; Jennersten, 1988; Rathcke, 2000). Disruptions that influence these animal vectors can have an impact on the reproductive success of tropical trees.

Studying plant-pollinator interactions is crucial for enhancing tree breeding and productivity. Such interactions are essential for the reproductive success of plants, particularly in outcrossing species. Tropical plant species with scattered and irregular distributions, self-incompatibility, dioecy, and high degrees of pollinator specialization are at increased risk of extinction if pollination is unsuccessful (Bawa *et al.*, 1985; Bond, 1994; Corlett, 2004). To ensure successful pollination of flowering plants, it is crucial to consider the habitat requirements of insect pollinators (Dar *et al.*, 2017b) and prioritize their conservation efforts. This will not only promote overall biodiversity (Dar *et al.*, 2016) but also contribute to the sustainability of ecosystems (Dar *et al.*, 2017c).

Human activities, such as habitat loss, misuse, and significant alterations in land-use patterns, have led to the decline of natural populations of numerous plant species. By comprehending the reproductive systems of plant species, it is feasible to predict their likelihood of survival and implement suitable conservation measures (Bernardello *et al.*, 2001). Fragmentation of habitats can disturb the relationships between plants and pollinators. *Acacia brachybotrya* and *Eremophila glabra* planted in linear vegetation saw less pollen deposition compared to those planted in nearby reserves, as reported by Jabeen and Bhat, 2013. According to Bond (1994) and Potts *et al.*, (2010), human activities are straining the mutualistic interactions between plants and pollinators. Pesticide usage, which contaminates pollinators (Brittain *et al.*, 2010; Brittain and Potts, 2011), in addition to habitat alteration and fragmentation (Steffan-Dewenter *et*

al., 2002; Harris and Johnson, 2004), and the introduction of non-native species (Brown *et al.*, 2002; Stout and Morales, 2009) are significant factors that contribute to the problem. These disturbances have the potential to decrease the number of pollinators and change the population dynamics of the remaining plants and animals (Bond, 1994).

Recently, there has been evidence of concurrent reductions in the variety of bees and plants that are pollinated by insects in Europe (Biesmeijer *et al.*, 2006), implying a practical relationship and reciprocal dependence between these two groups. Pollination effectiveness, in a broad sense, refers to the extent to which a flower visitor contributes to the distribution of pollen to the stigma or the successful production of seeds per visit. The correlation between diversity and connectivity can be ascribed to the impact of pollinator diversity on plants' seed production capacity (Klein *et al.*, 2003; Fontaine *et al.*, 2006). On the other hand, if insects that go to flowers depend on a range of flowers for food, a drop in the number of different plants could result in a decline in the variety of pollinators. In the absence of pollinators, numerous plants would face difficulties in producing seeds and reproducing. Additionally, the lack of plants that offer pollen and nectar would result in the loss of various animal populations, leading to a series of negative consequences across the ecosystems.

Insects are essential for the transfer of pollen, which allows genes to spread within a population by promoting crossbreeding among plants of the same species (van Ginkel and Flippin, 2020). Pollinators are greatly influenced by floral properties such as length, colour, odor, nectar, and other rewards (Faheem *et al.*, 2004). These characteristics dictate the effectiveness of pollination. For example, flowers that are pollinated by bees are usually vibrant in color, reflect light in the blue to violet range, and have markings that guide bees to the nectar during the day (Faheem *et al.*, 2004). In contrast, moths and bats are drawn to vibrant or pale-hued flowers that emit appropriate scents and possess nectar guides, which release nectar during night time (Zariman *et al.*, 2022). Butterflies are especially attracted to blooms that are pinkish or crimson (Abrol, 2012). Flowers emit distinct aromas to attract specific pollinators. Insect-pollinated flowers typically exude fragrances, while bird-pollinated blossoms

are often devoid of scent (Johnson and Govender, 2022). Nocturnally blooming flowers require potent, widespread floral scents to attract pollinators from a far.

Insect pollinators play a crucial role in preserving biodiversity, facilitating ecological activities, and offering resource conservation services for agricultural crops (Dar *et al.*, 2017a). These interactions are essential for human nutrition. The bee populations in agricultural areas have substantial obstacles as a result of limited and uninterrupted floral resources, alterations caused by human activities (Mir *et al.*, 2017), diseases (Ullah *et al.*, 2020), and inadequate nesting habitats. Many individual studies describe plant-pollinator interactions as quite specialized (Johnson and Steiner, 2000). However, community-based approaches often reveal that generalization is common across entire groups of plants and their potential pollinators (Waser *et al.*, 1996). This generalization leads to interaction networks that can tolerate extinctions and have backup systems (Memmott *et al.*, 2004; Ghazoul, 2005). In assessing the role of flower visitors as pollinators, the significance of each taxonomic group is influenced by two key factors: the frequency of flower visits and the effectiveness of pollination.

Flowering plants have developed a range of characteristics to enhance reproduction, including diverse colors, smells, flower structures, and incentives like nectar, which attract pollinators (Proctor *et al.*, 1996; Mayfield *et al.*, 2001). The plant-pollinator interactions have existed since the Cretaceous epoch, during which the foraging behavior of insects greatly enhanced the reproductive success of plants (Kearns and Inouye, 1997). Beetle-pollinated flowers, sometimes called cantharophily, usually have strong smells (either fruity or aminoid), do not have a specific shape, have nectar that is easily accessible (not hidden), and do not have markings to guide the beetles to the nectar (van der Pijl, 1961; Hingston and McQuillan, 2000). Bee-pollinated flowers, also known as melittophilous blooms, often feature small quantities of concealed nectar, possess nectar cues, are not red in color, provide a perch for bees, and display zygomorphic (bilateral) symmetry (van der Pijl, 1961; Hingston and McQuillan, 2000).

Sphingophily refers to flowers that are pollinated by hawkmoths. These flowers typically emit a pleasant fragrance, are white or green in color, have a slender floral tube or spur, lack a place for the hawkmoth to rest, have exposed anthers that can move during nocturnal anthesis, and contain a substantial amount of nectar. Additionally, these flowers have a deep dissection. (van der Pijl, 1961; Hingston and McQuillan, 2000). Butterfly-pollinated flowers, also known as psychophilous flowers, exhibit a range of colors, have a slender floral tube or spur, emit a mild scent, have delicate tissues, and contain anthers that are visible during daylight hours (diurnal anthesis) (van der Pijl, 1961; Hingston and McQuillan, 2000).

Chiropterophilous flowers, which are pollinated by bats, typically have a white or drab hue, are huge or form inflorescences, generate significant amounts of nectar, emit a disagreeable odor, and have exposed anthers during the night (van der Pijl, 1961). In addition, previous research has also examined the phenomenon of rodent pollination (Johnson *et al.*, 2001; Kleizen *et al.*, 2008; Wester *et al.*, 2009) and reptile pollination (Olsen and Valido, 2003). Fruit development in stone fruit crops relies on the presence of a solitary functional pollen tube. This process necessitates the transfer of pollen from a different bloom that is compatible and occurs at the appropriate moment. Therefore, it is crucial to have a varied population of insect pollinators in order to guarantee sufficient commercial production. Various insect pollinators include bees, wasps, ants, flies, butterflies, moths, and beetles (Dar *et al.*, 2016).

Nectar production in plants can yield both benefits and drawbacks (Brandenburg *et al.*, 2009). Nectar has several positive effects on pollinators. It can increase the number of times pollinators visit flowers, lengthen the time between visits, and extend the duration that pollinators stay at a flower. Nevertheless, there are drawbacks to the manufacturing of nectar, including the expenditure of energy required to create it (Southwick, 1984; Pyke, 1991; Brandenburg *et al.*, 2009). In addition, nectar has the potential to attract undesired visitors such as nectar robbers and specific microorganisms that consume nectar without contributing to the process of pollination (Brandenburg *et al.*, 2009). Additionally, there is a possible risk of cross-pollination between different species, where pollen from one species is transmitted to another

species that provides nectar. This process has the potential to decrease the reproductive success of the affected species (Brandenburg *et al.*, 2009). Pollinators produce a geographical mosaic of pollinator abundances since it has been shown that their distribution varies both temporally and spatially (Grant and Grant, 1965; Williams *et al.*, 2001; Herrera *et al.*, 2006; Johnson 2006). Such pollinator mosaics or changes in the pollinator ecotype may result from biotic (such as the availability of flowering plants) and abiotic (such as temperature and altitude) factors that can restrict the range and abundance of pollinators (Parmesan *et al.*, 1999; Geber and Moeller, 2006; Kerr *et al.*, 2015).

Pollinators frequently have specific climatic demands, therefore changes in their assemblages can arise from rising temperatures brought on by climate change (IPCC 2007). (Kerr *et al.*, 2015; Wilson *et al.*, 2007; Parmesan *et al.*, 1999; Schweiger *et al.*, 2010). These changes can have a substantial effect on the interactions between plants and pollinators (Biesmeijer *et al.*, 2006; Schweiger *et al.*, 2010). Nevertheless, the impact on pollinator-mediated selection and the resulting adaptive evolution of reproductive plant characteristics remains primarily theoretical due to a scarcity of experimental data. The tropical forest ecosystem found in Northeast India boasts a remarkable wealth of diverse plant and animal species. However, this region lacks comprehensive studies focusing on the functional dimensions of biodiversity. In particular, there is a notable absence of fundamental data regarding the specific pollinator species responsible for facilitating the pollination of valuable forest genetic resources (Kumar and Khanduri, 2016). Also, temperate forests, with their distinct ecological traits, require study due to their reliance on pollinators for the reproduction of plant species. Despite conducting a search, this lack of knowledge highlights the need for investigations to deepen our understanding of the connections involving this important plant species and its pollinators. Prioritising the protection of plant species with ecological and economical importance, including timber and non-timber forest products (NTFPs), and their pollinators in ecosystems is essential. Without this information, it becomes challenging to comprehend plant ecology, emphasising the urgency of future research efforts in this field.

1.8 Pollen viability and the influence of growth hormones on *in vitro* pollen germination

Pollen viability refers to the capability of the pollen to successfully complete post-pollination events, such as fertilization, on a compatible and receptive stigma. The viability and vigor of the pollen determines the rate of pollen quality. Although pollen samples may be viable at the time of shedding, their viability can deteriorate over a period, ranging from a few hours to several months. This decrease in viability is largely influenced by environmental conditions, especially temperature and humidity. For successful fertilization and seed production, the pollen must not only be fertile, but also viable at the time of pollination. Hence, pollen viability is crucial for successful fertilization and fruit and seed set (Shivanna, 2003).

Pollen performance plays a major role in pollination, as pollen viability and germination are crucial factors for flower fertilization (Parashuram *et al.*, 2021). The quality of pollen is assessed based on the viability and vigor of the pollen grain (Sulusoglu and Cavusoglu, 2014). "Pollen vigor" describes the rate at which pollen tubes develop and pollen grains germinate (Ottaviano and Mulcahy, 1989). Pollen vigor can be evaluated by *in vitro* pollen germination experiments, which measure the length of pollen tubes or the rate of germination over time (Shivanna and Ram, 1993). Pollen that cannot germinate usually shows poor tube growth, making it likely ineffective in fertilization (Sulusoglu and Cavusoglu, 2014).

Utilizing an appropriate technique to assess pollen viability is crucial when breeding fruit species (Radičević *et al.*, 2013). Pollen viability can be studied using various methods, with the choice depending on the crop species and the correlation between fertility and the test (Hanna and Towill, 1995). Dafni and Firmage (2000) conducted a comprehensive analysis of the literature on methods for assessing pollen vitality, elucidating the merits and drawbacks of each test. The reliability of the pollen staining method for most species has been questioned (Barrow, 1981). As a result, the *in vitro* pollen germination method is commonly employed as a more practical approach to assess pollen viability.

Pollen viability and germination are recognized as crucial determinants of successful fertilization and plant breeding through hybridization in stone fruits (Jamshidi *et al.*, 2021). The vitality of pollen has been assessed using in vitro germination experiments (Schoenike *et al.*, 1963). The technique of in vitro pollen germination is highly advantageous as it allows for elucidating the specific physiological and biochemical prerequisites necessary for the successful germination of pollen and subsequent growth of pollen tubes (Sanjay *et al.*, 2016). Among diverse techniques used to assess pollen viability, in vitro pollen germination is the most reliable method (Jayaprakash, 2018).

The germination medium and conditions may also vary between species and even between cultivars within the same species (Rosell *et al.*, 1999). The success of pollen in terms of its germinating ability can play a crucial role in determining not only fruit set but also the interactions between flowers and pollinators (Patel and Mankad, 2014). The process of pollen germination holds significant importance, impacting not only the successful development of fruits but also influencing the interactions between flowers and their pollinators. Pollen viability and germination are crucial determinants of successful fertilization, facilitating pollination and ensuring sufficient fruit output (Sutyemez *et al.*, 2011; Nikolić *et al.*, 2012). The process of pollen germination and subsequent pollen tube expansion plays a vital role in the fertilisation process and subsequent seed formation.

However, there is a possibility that pollen viability tests, despite being regarded as expedient and uncomplicated, may overstate the vitality and germination capacity of pollen grains (Gaaliche *et al.*, 2013). The variability of accuracy in viability tests has been noted by Rodriguez-Riano and Dafni (2000) across several species and cultivars. As an alternative, in vitro pollen germination has proven to be a very efficient and practical way to explore the useful applications of pollen biology. This opinion is consistent with the findings of Taylor and Hepler (1997) and is further substantiated by the research conducted by Grover (2016). It is essential to determine the extent of pollen viability at the time of natural pollination and in samples used for experimental studies

Evaluating pollen viability using in vitro germination is a more effective method than vital staining. If optimal circumstances are defined, the process for in vitro pollen germination would be exact and relatively easy (Taylor and Helper, 1997). The Brewbaker and Kwack medium (Brewbaker and Kwack, 1963) is the most frequently used culture medium for in vitro pollen germination. Variations in the amounts of sucrose and boron are required for optimal germination (Towill and Walters, 2000). The sugar in the medium serves as an energy source (Erfani *et al.*, 2017) and osmoticum (Matani Borkheyli *et al.*, 2021); and sucrose is generally used in pollen germination medium (Jayaprakash, 2018). Pollen has been germinated in a variety of media, which differs from species to species (Jayaprakash, 2018).

Pollen grains form inside the anther and are discharged as the anther matures. Once released, they become dry and metabolically inert (Kumar *et al.*, 2016). Pollen germination is influenced by water, amino acids, carbohydrates, boron, calcium, and growth regulators such as gibberellins, auxins, and kinetin. (Johri and Vasil, 1961; Pfahler, 1967; Singh *et al.*, 2002). Pollen germination is controlled by parameters such as species, medium composition, temperature, relative humidity, and duration (Stanley and Liskens, 1974). Sugars such as sucrose, glucose, fructose, and acidic polysaccharides are important components of stigmatic exudates in various plant species (McConchie and Knox, 1989). Pollen lifespan and sucrose levels are also factors that influence this variability (Pacini, 1996).

Gibberellins (GAs) are essential plant growth hormones that are intrinsic to plants and are needed for many processes such as seed germination, stem and leaf elongation, floral induction, anther development, and fruit and seed development. Gibberellins (GAs) have been found to affect both in vivo and in vitro pollen germination. Studies have shown the presence of GAs in growing pollen grains after pollination (Singh *et al.*, 2002). Indole-3-Acetic Acid (IAA) plays a crucial role in the sexual reproduction of plants by regulating the growth of gynoecia, ovary, stamen, and egg cells (Nemhauser *et al.*, 2000). As the level of IAA rises in the pistil after pollination, it boosts the capability for pollen tube growth (Aloni *et al.*, 2006). Kinetin enhances

pollen germination at low concentrations in *in vitro* culture, but inhibits pollen tube formation at high quantities (Soni and Bohra, 2021)

The reproductive biology of tropical and temperate tree species includes key aspects such as pollination, pollen generation, and pollen germination. These processes are generally associated with the effective development of fruits and seeds, demonstrating the reproductive ability of the species. Studying both the amount of pollen produced by trees and how well the pollen germinates in different environmental conditions can provide a better understanding of the reproductive capacity and adaptability of tropical and temperate tree species. The germination medium and conditions may also vary between species and even between cultivars within the same species (Rosell *et al.*, 1999). The success of pollen in terms of its germinating ability can play a crucial role in determining not only fruit set but also the interactions between flowers and pollinators. Studying reproductive ecology in temperate and tropical forests is crucial for understanding plant adaptation to diverse habitats, managing forest ecosystems, recovering threatened species, and sustaining crop yields, as reproductive processes are influenced by environmental variables and ecological interactions. Considering all the above factors, this study was conducted on *P. cerasoides* with the following key objectives:

1.9 Objectives

This study was conducted on *Prunus cerasoides* D. Don. growing at two contrasting location (Mizoram and Uttarkhand) with distinct forests i.e. tropical and temperate with the following objectives:

1. Comparison of annual variability in reproductive phenology of *Prunus cerasoides*
2. Assessment of pattern of anthesis, anther dehiscence, stigma receptivity, pollinators availability and mating system in *Prunus cerasoides*
3. Evaluate pollen production, pollen viability and *in vitro* pollen germination in *Prunus cerasoides*.

CHAPTER 2

Review of Literature

2.1 Reproductive phenology

Changes in climate impact the timing of reproductive events, as well as the geographic distribution of species, their functional characteristics, and their specific climatic preferences. Plant species with a greater range of exposure to annual precipitation (coldest month temperatures) have been observed to bloom earlier. Plant species that exhibit a broad range of precipitation during the wettest quarter have been found to have a longer reproductive cycle. The reproductive timing of tropical trees is determined by evolutionary factors and specific environmental conditions. The photosynthetic pathway also impacts the duration of reproduction. Reproductive phenology plays a key role in determining how successfully individual plants reproduce, as supported by the findings of Rathcke and Lacey (1985), Elzinga and colleagues (2007), and Craine *et al.* (2012a). Additionally, Craine *et al.* (2012b) noted that direct competition not only supports species diversity but also tends to limit differences in reproductive timing among species that grow together.

Changes in climate conditions can significantly influence reproductive phenological patterns (Anderson *et al.*, 2012). The initiation and length of the flowering phase are regulated by interconnected internal and external cues, including photoperiod sensitivity (Colasanti and Coneva, 2009). Reproductive phenology is shaped not only by environmental conditions but also by a plant's evolutionary lineage, photosynthetic pathway, and life history strategy (Cortés-Flores *et al.*, 2017; Munson and Long, 2017; Du *et al.*, 2015; Davies *et al.*, 2013). However, there has been no comprehensive investigation that demonstrates the relationship between climatic niches, phylogeny, plant function, and reproductive phenology. Life history may also play a significant role in influencing phenology as a result of allocation tactics (Lundgren and Des Marais, 2020). The intrapopulation behaviour of species, whether individual or group-

related, is a key aspect of studying the phenology of tropical plants. Physiological activity resumes in response to increasing day length and temperatures.

Recording the phenology of plant guilds or communities uncovers overarching trends in the timing of blooming, leaf emergence, and fruit production. Communities with staggered phenologies are often seasonal, and the individuals belonging to the same disperser species generally compete with each other and are frequently closely related. Tropical regions exhibit consistent annual cycles. Phenological variation is seen in all investigated tropical forests, both throughout seasons and across different years. The effects of seasonal variations in food availability on the composition and size of consumer populations are only now being investigated (Fleming *et al.*, 1987; Terborgh, 1987).

According to Baker and Baker (1936), the study of plant phenology reveals the differences between these two causes. Several deciduous species in seasonally dry tropical forests shed their old leaves well in advance of water stress (Wright and Cornejo, 1990), and a month before the start of rainfall, new leaves are generated (Frankie *et al.*, 1974a). Climate changes can trigger a plant's developmental response by adapting to a consistent environmental factor in order to optimise the timing of its life cycle events. The understanding of proximate and ultimate causes has been muddled by the lack of agreement between tropical climate cycles and physiological processes. Plants face various external biotic and abiotic stimuli that affect their ability to survive and reproduce, and each of these elements may influence certain phenological responses. Plants may benefit from enhanced herbivore avoidance, increased pollination success, and improved net photosynthesis by actively flushing and flowering during periods of high illumination.

Various *Prunus* species have shown a wide range of flowering and reproductive behaviors depending on where they're growing. For example, in Morocco, local almond genotypes (*Prunus dulcis*) were seen to flower and ripen earlier than commercial types (Sakar *et al.*, 2019), which points to the role of local climate in shaping growth cycles. Over in Indonesia, *P. cerasoides* has drawn interest due to its

unusual flowering. Some studies in Bali noticed that although the species flowers twice a year and goes through the whole bloom cycle, the flowers often fall off without developing fruit. Interestingly, changes in temperature and UV didn't seem to affect how many flowers developed (Octavia *et al.*, 2023). Similarly, long-term observations in the Cibodas Garden found that *P. cerasoides* also flowered twice a year, but the timing shifted from year to year (Kurniawan *et al.*, 2021).

In Algeria, climate appeared to directly influence *P. cerasus* trees, especially when it came to bud dormancy and the speed of fruit development. This was observed in two cherry varieties: Black Bigarreau and Sunburst (Hamed and Ghezlaoui, 2020). A completely different set of conditions was reported from the Iberian Peninsula, where *Prunus spinosa* and *Prunus mahaleb* bloomed at the same time. Still, *P. spinosa* ended up producing more nectar and attracting more pollinators, mainly bees from the Apidae family. The presence of pollinators made a big difference in fruit setting for both species (Gutián *et al.*, 1993). Looking closer at *P. mahaleb*, Jordano (1993) found that nearly half of the trees didn't produce pollen at all, making them male-sterile. Fruit set in these individuals was very low unless they received pollen from other trees. He also counted more than 40 different insect species visiting the flowers. In India, *Prunus domestica* trees flowered steadily over 40+ days during both 2009 and 2010 (Wadhwa and Sihag, 2019), showing a consistent seasonal rhythm.

Another interesting study on *Prunus africana*, a tree from sub-Saharan Africa, showed that individual trees varied a lot in when they flowered, though the main flowering peak occurred in mid-February (Were *et al.*, 2001). Kour (2018) explored six varieties of *Prunus salicina* in subtropical India and found that Kala Noki started flowering as early as February 3rd. Meanwhile, Alu Bokhara Amritsari had the longest bloom period. Bud development took around three to four weeks depending on the variety. Normasiwi (2015) studied three *Prunus* species in Indonesia over a four-year stretch. *Prunus costata* flowered the most frequently, up to four times a year, and often produced seeds. On the other hand, *Prunus arborea* rarely bloomed, and *P. cerasoides* bloomed twice a year but didn't set seeds often. Light played a role in triggering

flowering, while things like rain, temperature, and pollinators seemed to influence fruit development.

Chand *et al.* (2022) observed a noticeable advancement in the flowering of *Rhododendron arboreum* in a temperate forest of the Garhwal Himalaya, with blooms emerging five days earlier in 2017 compared to 2016. This shift was attributed to reduced winter precipitation, highlighting the species' sensitivity to climatic fluctuations. Interestingly, the flowering period coincided with increased activity of both bird and insect visitors, suggesting that synchrony between floral resources and pollinator presence may help buffer against potential mismatches and support successful reproduction.

Martínez-Peralta *et al.* (2022) investigated the reproductive ecology of *Dalbergia granadillo* and *Dalbergia stevensonii*, two native timber-yielding species of southwestern Mexico, and revealed key insights into their phenology and ecological limitations. Both species displayed synchronous and mass flowering, yet experienced high rates of floral abortion and low fruit set. Their small, fragrant, whitish flowers were primarily visited and pollinated by bees, although reproductive success remained low, possibly due to a scarcity of compatible individuals and the extensive removal of mature trees. The study emphasizes the critical role of bee pollinators and highlights how habitat degradation and illegal logging severely limit seed production and natural regeneration in these threatened species.

2.2 Mating system and reproductive strategies

The tree reaches a maximum height of 10 metres and has reddish brown bark that peels off in thin circular segments. The leaves are folded in a bud and have an ovate-lanceolate shape. They measure 3.5-8.5cm in size and have a smooth surface. The petioles measure 1.2-2cm in length, while the blooms are pinkish-white and have a diameter of 1.2-2.5cm. The flowers are supported by pedicels that are 0.5-2cm long. The flower has five lobes that are oblong and sharp. It also has five petals that are 1.2-1.5cm long and ovoid in shape. These petals are supported by the base of the calyx

tube. The fruits are either red or yellow and each fruit has a single seed. The flowering phase commences in October and concludes in December, followed by the fruiting phase from February to November. Honey is produced from the extraction of pollen and nectar, which serve as the raw materials. Advanced approaches are currently being used for the study of pollination (Faegri, 1978).

To preserve and enhance the wide variety of our world, pollination interactions are vital in supporting how approximately 200,000 species of flowering plants rely on pollination services provided by more than a hundred thousand other organisms. Pollination activity serves an essential ecological role across both cultivated and wild land-based ecosystems (Sharma and Abrol, 2014). Pollination serves as a foundational ecological function that supports the stability of both cultivated and natural land-based ecosystems (Sharma and Abrol, 2014). Pollination plays an essential role in maintaining species interactions within ecosystems, as its absence could lead to the breakdown of those ecological relationships (Nabhan and Buchmann, 1997; Kearns *et al.*, 1998). Consequently, there has been a significant increase in the amount of information available in literature regarding both wild and domesticated plant species.

The majority of flowering plants possess exclusively bisexual blooms (Lloyd, 1982), and their pollen is dispersed by a wide range of biotic and abiotic agents (Faegri and van der Pijl, 1979). The development of this sexual strategy is thought to result from natural selection aimed at improving the efficiency of cross-fertilization (Heithaus *et al.*, 1974). The processes of outbreeding and inbreeding in different sexual systems are regulated by numerous mechanisms such as hermaphroditism (including herkogamy, dichogamy, and heterostyly), gynodioecy, monoecy, dioecy, gynodioecy, androecy, and temporal dioecy (Bawa and Beach, 1981). Monoecy is a more sophisticated sexual system compared to andromonoecy and gynodioecy (Bertin, 1989). Wind-pollinated plants are prevalent in temperate regions and are also found in several entomophilous species inside tropical forests (Bawa and Beach, 1981). In bisexual flowers, the male and female phases are temporally offset at both the inflorescence and individual levels, driven by a highly synchronised flowering dynamics (Cruden and Hermann-Parker, 1977).

The alternating occurrence of male and female reproductive structures inside a single plant is described by Cruden (1988) as temporal dioecy. The allocation of biomass to male and female functions varies and can be influenced by the mating system (Cruden and Lyon, 1985). The environment is believed to have an impact on the manifestation of gender expression (Eriksson, 1987). Various methods were used to assess breeding systems (Tomlinson, 1974). The evaluation of breeding systems in the flora of tropical deciduous forests was conducted based on observations of floral sexuality and compatibility tests (Bullock, 1985). Normasiwi *et al.* (2023) evaluated open pollination, autogamy, geitonogamy, and allogamy in *P. cerasoides* and found that cross-pollination (allogamy) yielded the highest efficiency at 53.33%, with a corresponding fruit set of 24.17%, indicating a preference for outcrossing in this species.

Chauhan (2019) reported that *Eriobotrya japonica* exhibits self-incompatibility, as confirmed by hand pollination experiments, with the highest fruit set (58.5%) observed under open pollination, indicating a dependence on insect-mediated cross-pollination and the presence of facultative geitonogamy. Similarly, Neto (2013) found that *Bauhinia forficata* is predominantly self-incompatible, with cross-pollination producing twice the fruit set compared to open pollination. The study further indicated pollen limitation and reduced pollination efficiency, likely caused by habitat disturbance and an increase in geitonogamous events. A field investigation in Himachal Pradesh examined the impact of bee, open, hand, and controlled pollination on fruit set and quality in the sweet cherry. Bee and hand pollination resulted in the highest fruit set (approximately 70%), followed by open pollination. No fruit set was recorded in flowers excluded from pollinators, confirming the need for insect-mediated pollination (Bakshi *et al.*, 2018a).

Dongariyal *et al.* (2022) evaluated the pollination responses of two widely cultivated subtropical Japanese plum (*Prunus salicina*) cultivars, ‘Satluj Purple’ and ‘Kala Amritsari’, under northern Indian conditions. Six pollination treatments were tested, including self-pollination, open pollination (with cultivars in close and distant proximity), manual cross-pollination, supplementary pollination, and floral bouquet.

The results revealed strong self-incompatibility in ‘Satluj Purple’, which showed minimal fruit set and yield under self-pollination (3.3% and 2.0 kg/tree, respectively). In contrast, cross-pollination with ‘Kala Amritsari’ significantly improved pollen tube growth, fruit set (36.6%), and yield (28.0 kg/tree). ‘Kala Amritsari’ was found to be self-compatible, though the use of ‘Satluj Purple’ pollen as a pollinizer produced poor results. This review suggests that there is a greater abundance of material available in the breeding systems of trees and shrubs compared to that of forest herbs. Furthermore, a crucial aspect of plant breeding systems is that a species that is capable of self-fertilization can produce the majority of its seeds through cross-pollination. Nevertheless, cross-pollination can result in genetic inbreeding when it occurs between plants that share a recent common ancestor. Hence, aspects related to pollinator behaviour are central to the formation and regulation of a species’ breeding strategy.

2.3 Floral and pollination biology

Considering the reproductive output and the process of speciation, flowering plants and animals, particularly in relation to pollination, are of significant relevance. Flowers and pollinators have developed particular adaptations in their behaviour, physical characteristics, and structure. Within the field of reproductive ecology, there has been a specific focus on insects, particularly hymenopterans, lepidopterans, and dipterans, as the primary carriers of pollen. This emphasis was originally highlighted by Faegri (1978). Subsequent studies have identified beetles (Thien, 1974; 1980; Gottsberger, 1974; 1977; 1990), ants (Hickman, 1974; Beattie *et al.*, 1984), mosquitoes (Brantjes and Leeman, 1976), thrips (Løken, 1981; Ananthakrishnan, 1982; 1993; Velayudhan and Annadurai, 1986), and pollen-eating butterflies (Gilbert, 1972; De Vries, 1979) as recognised pollinators.

Vertebrates, specifically birds and bats, have been recognised as recent additions to the group of pollinators based on their functional role. Bat pollination has been documented in multiple investigations, including those conducted by Armstrong, (1979) and Marshall, (1983). Additional animals, including squirrels, monkeys, and marsupials, have also been classified as pollinators (Gottsberger, 1986; 1989). These

vertebrates are adapted for consuming flowers (Faegri and van der Pijl, 1979). Unlike insects, these vertebrates have longer lifespans, which means they need larger amounts of protein, as well as carbohydrates and lipids. As a result of this characteristic, pollination by animals has become a phenomenon in tropical regions. Observations were made of flower visiting by non-volant mammals visiting flowers, including diurnal mammals and monkeys.. However, it is uncertain whether these mammals play a role as pollinators (Gottsberger, 1986).

The coevolutionary relationship between flowers and pollinators is a manifestation of the ongoing process of evolution that we witness today. Nectar serves as the main lure and incentive for pollinators. According to Devlin *et al.* (1987), the secretion and concentration rate of flowers can cause variations in floral composition, flower age, flower density, temperature, and air humidity. The behavioural features of pollinators are influenced by sugar, amino acids, and chemical nectar (Percival, 1965; 1974; Baker and Baker, 1973). There appears to be a notable correlation between pollinators and sugar ratios (Baker and Baker, 1990). Floral species adapted to pollination by bats, birds, or hawkmoths generally produce nectar of lower viscosity than those pollinated by bees. Bees of considerable size, as well as hummingbirds and other similar birds, are drawn to nectars that have a high concentration of sucrose. According to Baker and Baker (1990), nectar from flowers visited by small bees, passerine birds, and neotropical bats tends to be rich in hexose sugars. Nevertheless, the total caloric value remains elevated. Some plants exude oil in their elaiophores as a replacement for nectar (Vogel, 1974; Simpson *et al.*, 1977). This suggests that by combining knowledge of nectar chemistry with the morphological and behavioural characteristics of flowers, it is possible to determine, even before seeing the plant in its natural environment, the most suitable pollinator to which it is adapted (Baker and Baker, 1990).

Several studies on *Prunus* species and other related woody trees have shed light on the intricacies of their floral biology, particularly in terms of anthesis timing, anther dehiscence, and floral morphology. In almond (*Prunus amygdalus*), Soodan *et al.* (1989) observed that flower buds began differentiating in the leaf axils as early as July. These buds remained dormant under protective pubescent scales through winter,

resuming growth in March when bud burst and anthesis took place within a span of about one week. The majority of flowers opened between 10:00 a.m. and noon, with anthers typically dehiscing either on the same day as anthesis or shortly thereafter.

The floral traits of *Prunus africana*, an endangered medicinal species native to Central Kenya, were studied by Were *et al.*, (2001). The flowers were found to be zygomorphic and opened between 08:30 and 13:00 h, attracting diurnal insect visitors such as honeybees and carpenter bees. These pollinators were frequently observed collecting nectar and pollen, suggesting active cross-pollination facilitated by daily anthesis and high floral attractiveness. In the case of subtropical plum (*Prunus salicina*), Kour (2018) recorded that flower opening in different cultivars peaked during the early afternoon, specifically between noon and 2:00 P.M., while anther dehiscence followed closely from late morning to early afternoon. Interestingly, stigma receptivity in all cultivars was noted to begin a day prior to anthesis, offering a broader window for effective pollination.

Feng *et al.* (2016) studied three plum cultivars ‘French’, ‘Victoria’, and ‘Stanley’ and noted that flowering occurred in early April with an average duration of 9–10 days. Each flower bore approximately 28 anthers, and pollen germination rates were around 27%. Among these, ‘Stanley’ stood out due to its higher pollen output and superior germination, indicating its suitability as a potential pollinizer. In contrast, while ‘French’ and ‘Victoria’ showed higher overall flower numbers, they produced comparatively less viable pollen. Majid *et al.* (2021) observed clear differences in the blooming behavior of both indigenous and exotic almond genotypes grown in Kashmir. While some varieties, like Mukhdoom and Shalimar, bloomed early in the season, others, such as Pranyaj and Merced, were noticeably late. The duration of flowering also varied, ranging from just four days in some genotypes to as long as nine in others, suggesting that flowering patterns are strongly influenced by genetic makeup.

Further observations on *Prunus domestica* by Wadhwa and Sihag (2019) revealed that anthesis typically initiated around 08:00 A.M. and peaked during midday, continuing

until late afternoon. This pattern remained consistent across multiple cultivars studied under semi-arid climatic conditions. Singh *et al.* (2019) studied nine genotypes of *Syzygium cumini* and reported significant variation in flowering and floral traits. ‘Selection 2’ showed the earliest flowering and highest stigma receptivity one day after anthesis. Anthesis and dehiscence occurred between 8:00–9:00 A.M. and 8:30–9:30 A.M., respectively. Dhiman (2014) investigated the reproductive biology of wild pomegranate (*Punica granatum*) in two populations from Himachal Pradesh. Flowers exhibited protogyny, with stigma receptivity beginning a day before anthesis and lasting up to three days. Anthesis occurred between 10:00 A.M. and 2:00 P.M. In the almond (*Prunus dulcis*), stigma receptivity increases as flowers mature, with peak receptivity occurring during the later stages of anthesis and supporting successful fruit sets (Yi *et al.*, 2006).

Chauhan (2019) investigated the phenology, floral biology, and breeding system of *Eriobotrya japonica* in Pathankot over a three-year period. Flowering began in mid-September and extended until late February, with anthesis occurring between 04:00 and 08:00 hours in acropetal succession. The species exhibited protandry, with stamens dehiscing between 04:30 and 08:40 hours and stigma receptivity peaking between 05:00 and 08:00 hours. Pollen viability was initially high (up to 85.7%) but declined sharply by late afternoon. Nagaar (2015) conducted an in-depth study on the reproductive biology of *Bauhinia vahlii* in two populations from Himachal Pradesh and reported that the species bears zygomorphic, bisexual flowers arranged in terminal corymbose racemes. Peak anthesis occurred between 6:00 and 9:00 am, followed by anther dehiscence 2 to 3 hours later. Stigma receptivity began around two hours after anthesis and continued for up to 48 hours, providing an extended period during which pollination could successfully occur. Neto (2013) investigated the reproductive biology of *Bauhinia forficata* in southeastern Brazil and reported that the species exhibits clear sphingophilous traits. Anthesis began at dusk, with flowers lasting approximately 18 hours. Pollen release occurred around 8:00 P.M., and stigma receptivity peaked at 11:00 P.M., consistent with a protandrous floral system.

Ansari and Davarynejad (2008) examined the flower microphenology of three Hungarian sour cherry cultivars (Botermo, Erdijubileum, and Sigany) under the environmental conditions of Khorasan, Iran, during 2005 and 2006. They observed that anther dehiscence initiated shortly after floral opening, with peak dehiscence recorded between 11:00 and 1:00 when temperatures ranged from 15°C to 20°C. The study also indicated that elevated temperatures enhanced the extent of anther dehiscence, reflecting the influence of thermal conditions on pollen availability.

There is increasing data indicating a substantial decrease in insect populations in both temperate and tropical regions (Janzen and Hallwachs, 2021; Sánchez-Bayo and Wyckhuys, 2019), leading to concerns about the future stability and ecological resilience of both natural ecosystems and human-altered environments (Ulyshen *et al.*, 2023). The significant and long-lasting decline in pollinators is a matter of great concern, as evidenced by several studies (Burkle *et al.*, 2013; Forister *et al.*, 2010; Powney *et al.*, 2019; Ulyshen and Horn, 2023; Barendregt *et al.*, 2022). Pollinators are estimated to enable the pollination of approximately 90% of flowering plant species around the world (Ollerton *et al.*, 2011) and support roughly 35% of the world's crop production by volume (Klein *et al.*, 2007). The decline in pollinator populations has garnered significant research attention due to their vital role in ensuring global food availability (Klein *et al.*, 2007) and in supporting the reproductive processes of native plant species (Cunningham, 2000; Vamosi *et al.*, 2006). This reduction in biodiversity is linked to a range of contributing factors, including the use of agrochemicals, the spread of pathogens, shifting climatic conditions, and the invasion of alien species (Barendregt *et al.*, 2022; Vanbergen, 2013).

Kitching *et al.* (2007) have documented the frequent visitation of flowers by insects of various types. Bees are widely recognised as the main pollinators in most ecosystems because of their specialised skills in collecting and distributing pollen (Danforth, 2007). However, numerous research (Silberbauer-Gottsberger and Gottsberger, 1975; Appanah and Chan, 1981; Mayfield, 2005; Epps *et al.*, 2015; Ssymank *et al.*, 2008; Sakai *et al.*, 1999; Appanah, 1981) have provided strong evidence that non-bee species are the primary pollinators for certain plants. Moreover, these non-bee species have a

crucial complementary role for numerous other plants. Rader *et al.* (2016) conducted a comprehensive synthesis of prior studies and reported that non-bee pollinators account for approximately 25% to 50% of total flower visitations. Furthermore, they discovered that these non-bees contribute to an increase in fruit set that beyond what bees alone can achieve.

While the importance of non-bee pollinator groups can vary depending on habitat and plant species, insects belonging to Diptera (such as flies), Lepidoptera (including butterflies and moths), and Coleoptera (beetles) play essential roles across a wide range of ecological system (Ulyshen *et al.*, 2023). Moths play a significant role as pollinators in tropical forests within the Lepidoptera group. They are particularly important for pollinating plant species that bloom at night. Various studies (Bawa, 1990; Nilsson *et al.*, 1987; Silberbauer-Gottsberger and Gottsberger, 1975) have confirmed their role in pollination. Moths serve as the main pollinating agents for a variety of woody and herbaceous plant species (Haber and Frankie, 1989). Within temperate ecosystems, insect-pollinated tree groups are recognized as vital floral resources during the early part of the spring season (Allen and Davies, 2022; Bertrand *et al.*, 2019; Urban-Mead *et al.*, 2023).

In some tree species, including *Prunus serotina* Ehrh. in North America, seed production may be limited by insufficient pollinator activity (McLaughlin *et al.*, 2022). In Costa Rica, Bawa *et al.* (1985) reported that more than 97% of rainforest tree species in the area rely on animals for pollination, with large-bodied bees contributing substantially. In Brazil, stingless bees (Meliponini) are known to be the sole floral visitors for approximately 40% to 90% of tree species, depending on the forest type (Kerr *et al.*, 1999). The study conducted in Pennsylvania found andrenid bees as the primary pollinators of black cherry plants. The presence of these bees was directly related to the number of seeds produced. Forest edges play a vital role as habitats for these bees, as they transport a substantially higher amount of black cherry pollen compared to other insects. The study emphasizes the significance of preserving environments that sustain these crucial pollinators for the healthy reproduction of black cherry trees (McLaughlin *et al.*, 2022). The research conducted in the Kashmir

valley revealed that there were a total of 41 insect species observed visiting plum flowering. Among these, the leading insect group was Hymenoptera, with a specific focus on Halictidae and Lasioglossum. The highest level of activity was observed between 10:00 A.M. and 14:00 P.M., most likely because there was an abundance of nectar. Conserving wild pollinators may enhance plum crop yield. (Dar *et al.*, 2020a).

2.4 Pollen production

Pioneering research by Pohl in the late 1930s laid the foundation for understanding pollen production across various plant species. His comprehensive studies examined the amount of pollen generated at different floral levels, including the anther, flower, inflorescence, and branch, in both herbaceous and woody plants (Pohl, 1937a, 1937b). Pohl reported considerable variability in pollen output, with herbaceous species such as *Mercurialis annua* producing up to 1.3 billion grains per plant. In contrast, woody plants like *Pinus sylvestris* produced between 152,000 and 162,000 grains per flower. Building on Pohl's work, Erdtman (1954b) expanded the study to include 19 plant species, establishing a relative pollen production index and highlighting the trend towards increased pollen production in wind-pollinated plants. While the overall amount of pollen produced by a plant can be influenced by a range of factors (Stanley and Linskens, 1974) and may vary between years (Rogers, 1993), determining the exact quantity of pollen per plant remains essential. Such analysis is important not only for aerobiological studies but also from an agronomic perspective, as successful seed production is often linked to pollen output (Cour and Van Campo, 1980; Faegri and Inversen, 1989).

Pohl's work in the 1930s represents a pioneering and highly thorough investigation into pollen production in plants (Pohl, 1937a; 1937b). Reddi and Reddi (1986) conducted a study on pollen production in 82 angiosperm species and found noticeable variation even among species within the same genus. They reported that species outside the Poaceae and Cyperaceae families generally produced larger quantities of pollen, indicating a possible link between pollen output and reproductive strategy. Species with higher pollen production were predominantly cross-pollinated, whereas

those with lower output were usually self-pollinating or reproduced through apomixis. According to Khanduri (2014), the annual pollen production per tree in *Lagerstroemia speciosa* during a mass production year ranged from 6.4×10^8 to 1.3×10^8 . This indicates that higher pollen production correlates with a higher percentage of fruit set.

Rojas-Gómez *et al.* (2023) carried out a study examining pollen grain counts per anther across 57 olive cultivars over a three-year period. They used Generalized Linear Models (GLM) and K-means clustering to analyze the data. Cultivar identity explained 51.3% of the variation in pollen production, while annual effects contributed only 0.3%, and the interaction between cultivar and year accounted for 8.4%. Although the fruit load from the previous season and its interaction with the year were statistically meaningful, they accounted for just 1.5% of the observed variation. The cultivars were grouped into four clusters according to their pollen output, with one cluster consisting of male-sterile types, likely due to genetically inherited traits. Bai and Subba Reddi (1980), along with Reddi and Reddi (1986), investigated pollen output per anther across various flowering plant species. Agnihotri and Singh (1975) emphasized that pollen production can differ considerably not only between species but also among those belonging to the same genus. Their study demonstrated a positive association between pollen output and anther size, and a negative association with the size of the pollen grains. Consequently, species possessing relatively larger anthers and smaller pollen grains were found to produce higher quantities of pollen.

Smart *et al.* (1979) conducted a study to quantify pollen output across 30 grass species. They assessed pollen quantity at both the anther and spike levels (Smart *et al.*, 1979). To estimate the total pollen output per area, they calculated spike density per square meter in species belonging to the Gramineae family (Smart *et al.*, 1979). For *Lolium perenne*, the study recorded an estimate of 2.11×10^{13} pollen grains per hectare per season (Smart *et al.*, 1979). Hyde and Williams (1946) estimated pollen production in *Plantago lanceolata* by determining how many inflorescences occurred within a square meter, the typical number of open flowers per inflorescence, and the mean pollen count per flower. Based on this approach, they reported an average of 40×10^6 grains of pollen per square meter. Nair and Rastogi (1963) conducted research on the

pollen output of many species that are associated with allergies in people. Their findings included *Chenopodium album*, which produced approximately 133 pollen grains per anther, and *Morus alba*, with a considerably higher output of around 23,388 pollen grains per anther.

Agnihotri and Singh (1975) reported that *Cynodon dactylon* produced approximately 800 pollen grains per anther, while *Secale cereale* yielded about 13,000. They suggested that total pollen production is closely associated with anther dimensions, specifically its length and size, estimating between 700 and 1,200 pollen grains per millimetre of anther length. Assessing the overall pollen output of a plant is important not only for agricultural applications but also for studies in aerobiology, since seed formation often relies on sufficient pollen availability (Cour and Van Campo, 1980; Faegri and Iversen, 1989). However, the amount of pollen produced by a plant is subject to multiple influencing variables (Stanley and Linskens, 1974) and can fluctuate annually (Rogers, 1993).

Holm (1994) showed that increasing the amount of pollen added to *Betula* can result in a higher yield of seeds. Erdtman (1943) also examined several European species in relation to this characteristic. The main species responsible for creating airborne pollen are mostly those with wind-pollinated blooms. However, it is possible to collect pollen from Entomophilous species during atmospheric research as well. Hyde and Williams (1944) found that the majority of species were wind-pollinated, comprising approximately 93.5%, while only 6.5% relied on insect pollination. Hyde (1952) has provided intriguing statistics on pollen generation observed throughout a 6-year timeframe in Cardiff.

Wind-pollinated plants generally generate a greater quantity of pollen than insect-pollinated plants, regardless of whether it is quantified per stamen, per flower, or per inflorescence (Proctor *et al.*, 1996; Cruden, 2000). Therefore, the amount of pollen generated is crucial in ensuring successful pollination (Allison, 1990). The anemophilous species exhibit a notable disparity in pollen output, as previously emphasized. Air temperature is a significant environmental component that has a

strong impact on both large and small-scale environments (Moore *et al.*, 1991; Faegri and Iversen, 1989).

Temperate trees, which are commonly found among wind-pollinated species, disperse considerable quantities of pollen into the atmosphere each year. This is an important factor for their reproductive success in forest ecosystems. These species rely substantially on the extensive dissemination of pollen via the air for successful fertilisation, which requires significant pollination efforts powered by wind (LaDeau and Clark, 2006). In temperate locations, a wide range of tree species, including conifers, show year-to-year fluctuations in pollen production. This variation has a direct effect on the rate at which fruits are formed, and seeds are produced, as demonstrated in studies like Shibata *et al.* (2002). These oscillations highlight the variability in plant reproductive strategies and their reactions to environmental signals.

Joppa *et al.* (1968) conducted a study on *Triticum* varieties, measuring the quantity of pollen released into the atmosphere and examining the percentage of anthers that were shed during flowering. This study yielded significant findings regarding the mechanisms of pollen distribution in wheat species. *Prunus spinosa* L., commonly found in temperate zones, exhibits efficient pollen production, varying seasonally with 0.23 mg per flower and 1.99 g per 1 m² of shrub surface. Analysis of its pollen reveals high protein (22.1–34.2%) and lipid (2.7–3.6%) and it contains beneficial fatty acids such as omega-3 and omega-6, with potassium being the primary mineral, followed by calcium and magnesium. The pollen of *P. spinosa* is a significant component of bee pollen, accounting for 89.1–98.2% of the pollen of *Prunus*, emphasizing its role in supporting early spring pollinator diets (Dmitruk *et al.*, 2023). Environmental conditions significantly influence the pollen production of various tree species, as reported by Scamoni, (1955). The study identified marked fluctuations in the timing of pollination, the volume of pollen released, and the years in which pollen production was at its highest among various deciduous species, as well as in spruce and pine. Despite these findings, research on the overall quantity of pollen produced by individual plants remains limited.

In trees and shrubs, pollen production is seldom estimated at larger scales such as per individual tree, per canopy area, or per unit of land surface, primarily because it is difficult to generalize data from small-scale observations (Rogers, 1993; Moore *et al.*, 1991). Animal facilitated pollination necessitates a substantial quantity of pollen grains to guarantee successful pollination, as bee-pollinated plants benefit from the abundance of pollen production (Kremen *et al.*, 2002). Pollen production now determines the success of pollination. Classifying plants based on their pollen production would have practical advantages as well as intellectual significance. Quantifying the pollen production of different plant species would be valuable in assessing the suitability of plants as a food source for both honeybees and wild bees. Pollen production is essential for the regeneration of plant populations in tropical forest ecosystems and strongly impacts the reproductive success of species (Schwartz *et al.*, 2017). Producing a high volume of pollen enhances the chances of sufficient pollen reaching the stigma, which supports greater fruit and seed set. This, in turn, influences plant abundance and the capacity for population maintenance. Moreover, it contributes to improving the success rate of the plant's mating system (Khanduri *et al.*, 2015b).

2.5 Pollen viability

Pollen viability, as described by Shivanna *et al.* (1991), refers to the capacity of a pollen grain to successfully transfer male gametes to the embryo sac after a compatible pollination event. Assessing pollen viability in this sense is laborious, time-consuming, and not always possible. Pollen quality testing is essential in various settings, including assessing the reproductive potential of parent lines and hybrids in breeding and genetic studies, as well as tracking pollen viability during storage conditions (Heslop-Harrison *et al.*, 1984). *In vitro* germination involves cultivating pollen on an artificial medium and then assessing, under microscopic observation, the percentage of grains that successfully form pollen tubes within a set period. This percentage serves as an indicator of the viability of the pollen sample, as noted by Abdul-Baki (1992), Ganeshan and Parfitt (1989), Luza and Polito (1988), and Shivanna *et al.*, (1991).

The reliability of germination assays is compromised by erroneous pollen germination in artificial conditions (King, 1960). Nevertheless, numerous comparison studies (Pearson and Harney, 1984; Shivanna *et al.*, 1991; Parfitt and Ganeshan, 1989; Werner and Chang, 1981) resulted in consistent recommendations for germination. Germination assays have the capacity to offer the most accurate means of determining pollen viability (Heslop – Harrison *et al.*, 1984). The chemical compound 2,3,5-Triphenyl-tetrazolium chloride (TTC) has been widely applied in pollen viability testing, with its utility critically evaluated in early studies by Smith (1951) and Cook and Stanley (1960). However, research by Oberle and Watson (1953) indicated that TTC may not serve as a reliable marker of pollen viability in species such as peach, apple, grape, and pear. In contrast, Widrlechner *et al.* (1983) studied TTC's effectiveness on deciduous azalea pollen, Weiner and Chang (1981) focused on *Prunus persica*, while Sarvella (1961) and Aslam *et al.* (1964) examined cotton pollen, all of whom reported that TTC acted as a quick and effective indicator of pollen viability. Furthermore, Abdul-Baki (1992), Parfitt and Ganeshan (1989), and Pearson and Harney (1984) noted that sucrose is the most commonly employed carbohydrate in in vitro pollen germination assays.

The sugar concentration used in germination media varies significantly. Vantheghem (1869) observed that the pollen of around thirty different species can easily germinate in water without the presence of sugar. Branscheidt (1930) found that *Cornus*, *Helleborus*, and *Cannabis* pollen only germinated when exposed to sugar concentrations of 70-80%, which is in contrast to other conditions. In general, sugar concentrations exceeding 40% hinder the formation of pollen tubes, but concentrations below 2% result in an increased likelihood of the tubes bursting (Brewbaker and Mazumdar, 1961). The optimal sucrose content for most plant species can only be determined within a wide range (Kim *et al.*, 1985; Leduc *et al.*, 1990; Pinny and Polito, 1990; Visser, 1955).

According to findings by Katara and Mankad (2012), *Datura metel* L. pollen demonstrated optimal germination in a medium containing 7% sucrose. In a previous study by Mondal and Ghanta, (2012), it was shown that 92% of pollen germinated and

produced pollen tubes that were 1144 μm long in a 15% sucrose solution with the addition of 100 ppm boric acid for *Lawsonia inermis*.

Gibberellins (GA_3) are naturally occurring hormones that serve as key regulators in plant physiology and contribute significantly to overall plant development (Acar *et al.*, 2010). These hormones are involved in numerous developmental processes, including seed sprouting, formation of trichomes, stem and leaf elongation, initiation of flowering, anthers development, and the production of fruits and seeds (Hedden and Phillips, 2000; Ross *et al.*, 1997; Yamaguchi *et al.*, 1998; Pharis and King, 1985).

GA_3 is present in actively developing pollen following fertilization, and several research efforts have reported its influence on pollen tube development under both in vivo and in vitro conditions (Singh *et al.*, 2002). The response of pollen germination and tube extension in vitro to GA_3 can vary depending on species and concentration. It may enhance, suppress, or show no effect at all, as documented in studies by Acar *et al.* (2010), Bhandal and Malik (1979), Setia *et al.*, (1994), and Viti *et al.*, (1990). The presence of a high quantity of GA_3 was discovered to have inhibitory effects, as reported by Kumar *et al.*, (1981). IAA, IBA, GA_3 , and Kinetin were found to have either a stimulating or inhibiting effect on germination and pollen tube expansion, as observed by Khan *et al.*, (1999). According to Khan *et al.* (1999), IBA at a 0.0001% concentration was most effective in stimulating the germination of pollen in species such as *Brassica campestris*, *Stellaria media*, *Phaseolus lablab* and *Euphorbia helioscopia*. The high concentration of NAA in the compound prevented the in-vitro pollen germination of Almond, while the addition of boron in the germination medium stimulated the germination process (Imani *et al.*, 2013).

Shamsolshoara *et al.* (2023) carried out an investigation to assess the viability of pollen and its ability to germinate in seven different cultivars/genotypes of *Prunus* spp. The viability was evaluated using the IKI method, whereas germination was performed using various sucrose doses. The results demonstrated different viability rates among cultivars, with 'Angelano', 'Bukhara', and 'St. Julien' exhibiting the greatest rates. The germination rates varied greatly according to the sucrose concentrations, with

'Angelano' exhibiting the highest rate and 'Formosa' showing the lowest rate. There was a strong positive connection ($r = 0.79$) between the viability of pollen and its germination.

Sulusoglu and Cavusoglu (2014) focused on evaluating pollen viability and in vitro germination across seven distinct genotypes of cherry laurel (*Prunus laurocerasus* L.). They applied two different viability tests: 2,3,5 triphenyl tetrazolium chloride (TTC) and iodine potassium iodide (IKI), and assessed germination using a medium containing varying sucrose level, ranging between 0% and 20%. Pollen grains that successfully germinated were counted at specific intervals of 1, 4, 6, 10, 12, 24, and 48 hours in order to monitor the progression of germination over time. Differences in the ability of pollen to fertilize, as determined by the TTC and IKI staining tests, were identified among different genotypes. Although the IKI test produced a higher percentage of pollen with visible paint, the TTC staining procedure provided more precise assessments of pollen vitality. The germination rates were highest for most genotypes when a sucrose concentration of 15% was used. Furthermore, the rates of pollen germination exhibited a significant rise following a 6-hour period of incubation in the culture medium.

According to Sorkheh *et al.* (2011), germination was assessed in eight native Iranian wild almond species over the course of a 24-hour period at temperatures spanning 10 °C to 50 °C, increasing in 5 °C increments. There was a large variation in pollen germination among different species. *P. orientalis* had a germination rate of 60%, whereas *P. scoparia* had a germination rate of 98%. The temperature response exhibited a modified bilinear pattern, with species-specific cardinal temperatures. T_{max} , which represents the maximum percentage of germination, has been identified as a critical determinant in the tolerance of pollen germination to temperature.

Three *Prunus* interspecific hybrids were evaluated for pollen viability and in vitro germination Bavanat (*Prunus armeniaca* crossed with *Prunus salicina*) and two genotypes, Shiraz and Shahriar, which resulted from a cross between *Prunus cerasifera* and *Prunus armeniaca*. Standard staining techniques were used to

determine pollen viability, and pollen grains were incubated at controlled temperatures for germination at varying sucrose concentrations (150 to 250 g/l). Shahriar demonstrated the highest level of pollen viability and in vitro germination rate, whilst Bavanat exhibited the lowest. Germination rates were generally enhanced by sucrose concentrations ranging from 150 to 250 g/l, whereas concentrations over 150 g/l adversely affected Bavanat. These results highlight notable variations in pollen viability and germination between the hybrids, with Shahriar exhibiting better results (Shamsolshoara *et al.*, 2022).

The process of pollen germination was investigated in five different peach cultivars (*Prunus persica* (L.) Batsch): Dixired, Redheaven, Gloheaven, Suncrest, and Summerset. Multiple variables were evaluated, including the content of sucrose (10%, 15%, 20%), the age of the seeds at the time of planting (fresh, 7 days old, 14 days old), the temperature (10 °C, 15 °C, 20 °C, 25 °C), and the duration of incubation (3h, 6h, 12h, 24h). The germination of pollen was influenced by genotype, sucrose content, sowing time, and temperature. Among the several cultivars, the highest germination rates were seen when using fresh pollen, a sucrose concentration of 10%, incubation at 15 °C, and a duration of 12 hours. The duration of incubation did not have an impact on the process of germination. These findings highlight the importance of thoroughly evaluating various parameters to enhance the in vitro germination of pollen in peach cultivars (Milutinović *et al.*, 2006).

Flowers in various stages of development (anthesis, pre-anthesis, and post-anthesis) were gathered in the morning. The vitality and germination of pollen were evaluated using aniline blue staining and an in vitro germination medium. The pollen extracted from flowers that had just opened (at the stage of anthesis) exhibited the highest levels of viability and germination rates. Specifically, it had the greatest number of viable pollen grains (33.00), a viability percentage of 35.40%, and a germination count of 4.67. Germination rates were significantly lower (3.08) in post-anthesis flowers compared to pre-anthesis blooms, when no germination was seen. This emphasizes the significance of utilizing recently bloomed flowers for evaluating pollen performance and its germination potential in hybridization initiatives (Baba Nitsa *et al.*, 2020). This

study assessed the *in vitro* germination and survivability of brinjal pollen under both normal and cold storage conditions. Pollen germination was assessed in a controlled laboratory setting by placing pollen grains in different quantities of sucrose, boron, and agar medium and incubating them at a temperature of 25 °C for a duration of 3 hours. Acetocarmine staining was employed to assess the vitality of pollen. A total of eleven treatments were administered, encompassing varied levels of sucrose, boron, and agar concentrations, in addition to a control group treated with distilled water. The utilization of a solution containing 1% agar, 12% sucrose, and 300 ppm boron led to the most successful initiation of growth in recently collected pollen. The germination percentage was lowest in agar-free media with varying amounts of sucrose and boron, and no germination was seen in pure water. The germination percentage of fresh pollen was the highest (95.00%) *in vitro* but declined with longer storage duration. Pollen stored in a refrigerator showed improved germination compared to that kept under room temperature conditions (Ginoya *et al.*, 2022).

Gencer *et al.* 2023, undertook a study to assess the pollination capabilities of three different olive cultivars: Domat, Gemlik, and Sarı Ulak. At three stages of flowering, 25%, 50%, and 75% of the flowers were open when they measured the rate of viable pollen, success of germination, and the quantity of pollen produced. According to the results of their three-year investigation, Sarı Ulak had the lowest pollen viability percentage (77.41%), whereas Gemlik (81.51%) and Domat (81.50%) had the greatest percentages. Domat exhibited the highest percentage of pollen germination, reaching 59.85%. Gemlik followed closely with a rate of 59.74%, while Sarı Ulak had the lowest rate at 52.12%. Although Sarı Ulak has a large pollen production per flower (329,046), its viability and germination rates are comparatively lower than those of Gemlik and Domat. The values of Gemlik and Domat cultivars were quite similar. Additionally, compared to the 25% flowering time, the study found that higher levels of viability, germination, and pollen output were observed during the mid and late flowering stages (50% and 75%) compared to the early bloom (25%).

In their study, Uzun *et al.* (2023) examined the viability and germination of pollen in four apricot cultivars, namely "Stark Early Orange" (SEO), "Harleyne," "Harcot," and

"Zard," all of which possess resistance against sharka disease. Pollen viability was evaluated using TTC, while germination was examined using an agarose-sucrose medium. SEO exhibited the highest viability rate at 57.8%, "Harleyne" demonstrated the most successful germination rate at 69.8%, whereas "Harcot" displayed the lowest viability rate at 28.3% and germination rate at 19.8%. The variation in pollen quality across different cultivars emphasizes their potential in breeding efforts, which are essential for enhancing disease resistance and increasing apricot production.

2.6 Pollen ovule ratio

The pollen-ovule (P/O) ratio is a key floral characteristic that offers insights into a plant's reproductive strategy, shedding light on its mating behaviour and system (Cruden, 1977; Preston, 1986; Bosch *et al.*, 2001; Bennet, 2001; Jürgens *et al.*, 2002). Several studies have explored the relationship between P/O ratio and seed size, though typically based on limited datasets (Preston, 1986; Bosch *et al.*, 2001; Shaanker and Ganeshaiah, 1984; Lopez *et al.*, 2000; Mione and Anderson, 1992). Götzenberger *et al.* (2006) demonstrated the broader applicability of this association through analysis of approximately 300 species. Additionally, their investigation uncovered that this association is not consistent throughout all taxonomic groups; certain groups demonstrate a more pronounced correlation, and the regression slopes vary among them. These variances are probably a result of differences in the pollination and ecological strategies that have developed in various taxa.

The classic approach for determining pollen-ovule ratios involves the manual counting of ovules and the estimation of pollen grain numbers. This method was devised by Cruden, 1977 and is known for its simplicity and cost-effectiveness. Nevertheless, creating an accurate predictive model for pollen-to-ovule ratios could offer significant advantages, such as saving time and enabling simultaneous estimation across numerous species. Nepal *et al.* (2023) observed that the pollen-ovule ratio (P/O) per flower rose considerably with elevation in Yulong Snow Mountain (2709–3896 m a.s.l.) after studying 84 insect-pollinated flowering plants. The increase in pollen count was the result of a rise in pollen grain quantity, while ovule count remained unchanged.

This suggests that there has been an adaptation to cope with the more unpredictable pollination conditions found at higher elevations. There are strong indications from the phylogenetic analysis that P/O is a property that has been conserved throughout evolution.

Pollen-ovule ratios (P/O) have been utilized for the estimation of plant breeding systems. The connection between pollen-ovule ratios and reproductive systems is often interpreted through the lens of sex allocation theory, which suggests that P/O reflects pollination efficiency (Gallardo *et al.*, 1994). Furthermore, factors like a plant's growth habit and biological traits also affect P/O ratios (Alarcón *et al.*, 2011). Higher pollen-to-ovule ratios are linked to cross-pollination, whereas lower ratios are associated with self-pollination (Cruden, 1977). Species that possess specialized structures for packaging pollen, such as compact pollen clusters like pollinia, polyads, or sticky threads, tend to have lower P/O ratios due to efficient pollen transfer. Conversely, species that offer pollen as a reward show higher P/O ratios than those that produce nectar, as more pollen is typically consumed (Cruden, 2000).

Angiosperms have a diverse variety of pollen and ovule counts per flower, highlighting the significance of these reproductive spores (Burd, 2011). A frequently seen pattern is the ratio of pollen to ovules per flower, known as the P/O ratio. This ratio is commonly applied as an approximate indicator of the reproductive strategy (Cruden, 1977). When self-pollination occurs, whether by geitonogamy or autogamy, it results in pollen grains competing within a limited space. The competition among nearby mates affects the allocation of sexes, leading to a preference for more female investment in reproduction and, as a result, a reduced P/O ratio. According to Shanker and Ganeshiah, (1984), wild species have larger P/O ratios than domestic species due to the increased risks of pollination faced by wild species. Furthermore, they noted a direct relationship between the decline in pollen-to-ovule ratio and the increasing maturity of *Croton* plants, as well as the likelihood of pollen grains successfully reaching the stigma. Alarcón *et al.* (2011) have shown the relationship linking pollen-to-ovule ratios with reproductive strategies in certain plant families. Etcheverry *et al.* (2012) examined pollen-ovule values in 21 Leguminosae species and categorized 15

of them as obligatory xenogamous, even though some had previously been identified as facultative xenogamous. The researchers determined that the variability of P/O (pollen/ovule) ratio is controlled by the taxonomic classification and pollination approach. The P/O ratio, which illustrates the relationship between breeding practices and particular floral characteristics, has generally been used to quantify plant breeding systems.

Khanduri *et al.* (2015b) found that the pollen-to-ovule ratio indicates that *Mesua ferrea* and *Schima wallichii* follow a cross-pollination strategy. In contrast, *Bombax ceiba*, *Erythrina stricta*, and *Lagerstroemia speciosa* fall under the xenogamous group as outlined by Cruden (1977). However, *B. ceiba* and *E. stricta*, which are bird-pollinated and offer nectar as a reward, show a lower pollen-to-ovule value than the insect-pollinated species *M. ferrea*, *S. wallichii*, and *L. speciosa* (Cruden, 2000). The observed negative connection between the quantity of pollen grains per flower and fruit set in *B. ceiba* and *E. stricta* indicates that fertilization pollen mainly comes from other flowers (geitonogamy or xenogamy) rather than from the same flower (autogamy). Species that depend on outcrossing often experience more pronounced pollen limitation than those capable of self-fertilization, as self-pollination does not facilitate reproductive success in outcrossers (Burd, 1994; Larson and Barrett, 2000; Saumitou-Laprade *et al.*, 2010).

The P/O ratio in hermaphroditic plants is an important factor in determining the mating system Khanduri *et al.*, 2015b. A higher P/O ratio suggests a higher probability of outcrossing (Khanduri *et al.*, 2015b). Within the realm of flowering plants, which typically possess both male and female reproductive organs, the degree to which seeds are fertilized by their own pollen or pollen from other plants varies greatly among different species. This variation can range from mostly self-fertilization to solely relying on pollen from other plants for fertilization (Goodwillie *et al.*, 2005). The breeding system, whether skewed toward outcrossing or selfing, has a major influence on the genetic structure of populations, the extent of gene movement, the size of reproductively effective populations, and the likelihood of inbreeding depression (Barrett and Harder, 2017).

Research on the development of mating systems has mostly examined the reasons that encourage self-fertilization. These aspects include ensuring reproduction in conditions with restricted pollen transmission and the genetic advantages of self-fertilization in populations with minimal negative effects of inbreeding (Butcher *et al.*, 2011). Several facultative xenogamous species are commonly observed in climax or other stable environments. These species may display delayed self-fertilization, possess self-compatibility, and have developed mechanisms for cross-pollination. Nevertheless, the pollination activity of these organisms may be restricted or inconsistent (Cruden and Lyon, 2019). *Chaenomeles speciosa* demonstrates an obligate xenogamous reproductive strategy, as categorized by Wan *et al.* (2024). This classification aligns with observations by Galloni *et al.* (2007) that species exhibiting xenogamous reproductive activity typically have high pollen/ovule (P/O) values, indicative of limited pollen transfer efficiency. The study concluded that the P/O ratio serves as a reliable indicator of a species' breeding strategy, as confirmed by their productivity analyses. Conversely, the low P/O ratio observed in *Clerodendrum inerme* suggests a high efficiency of hawkmoth pollination in this species (Primack *et al.*, 1981).

2.7 Pollinators availability

The blooming period of *P. cerasoides* commences in October and extends until December. The pinkish-white flowers of the plant provide nectar and pollen, which serve as important foraging materials for pollinators like bees (Gaur and Nawani, 1989; Sharma, 1970; Crane *et al.*, 1984). During its peak flowering season, large groups of bees collect nectar and pollen from the trees in abundance. Pollinators are important for seed production and reproductive success in tropical trees that rely on cross-pollination. They also help in maintaining genetic diversity within a population. Animals may visit open flowers for various purposes, including feeding on nectar or pollen (Kevan and Baker, 1983), seeking shelter (Sakai, 2002), and preying on other floral visitors (Dukas, 2003). An assessment of the presence of pollinators in various agro-climatic regions would provide useful insights into the intricate processes of pollination at the species, population, and community levels.

Biotic pollination has been identified as a crucial factor in the diversification of certain significant plant and animal species (Dodd *et al.*, 1999). Species interactions have a crucial role in the structural, functional, and evolutionary dynamics of communities in tropical trees. This has been demonstrated by studies conducted by Paton and Ford, (1977), Gryj *et al.*, (1990), and Linhart *et al.*, (1987). The symbiotic association between plants and pollinators originated during the Cretaceous era, when insects started to get nourishment from flowers, resulting in enhanced reproductive efficacy for flowers through the transfer of pollen by insects. Pollinators are essential for the survival of these plants, similar to the significance of light and water (Levin, 1971). Presently, a minimum of 68% of blooming plants are dependent on insects for the process of pollination, but some rely on birds and mammals.

Despite the richness of flowering plant diversity, our understanding of how these species reproduce and interact with pollinators and seed dispersers remains limited. Studies addressing such ecological relationships are comparatively few, highlighting a significant gap in current botanical research. In the mountainous forest regions of Southeast Asia, Zosteropidae birds frequently present in high densities are believed to contribute significantly to pollination. Ali and Ripley (1999) are credited with significantly facilitating the transfer of pollen amongst a diverse range of flowers. The Zosteropidae family can play a vital role as pollinators in montane forests in Southeast Asia, where they can be found in large numbers. The Zosteropidae family can play a vital role as pollinators in montane forests in Southeast Asia, where they can be found in large numbers. Additionally, the Nectariniidae family consists of two key which includes sunbirds, and the *Dicaeini*, which consists of flowerpeckers sunbirds (Cheke *et al.*, 2001). *Arachnothera longirostra*, a sunbird species, can cover a significant distance of up to 5 km while foraging and transferring pollen in the Malaysian jungle (Wells, 1988). Sunbirds have been observed visiting several types of flowers (Cheke *et al.*, 2001; Subramanya and Radhamani, 1993). However, they often access nectar by piercing the base of the corolla tube (Roberts, 1992; Ali, 1932). The Loranthaceae family is typically involved in situations of verified or strongly suspected successful pollination, as noted by Van Leeuwen, (1933) and Davidar (1985). Van Leeuwen (1933) suggested that some high-altitude *Rhododendron* species may be pollinated by

sunbirds. Additionally, Momose *et al.* (1998) identified sunbirds as the principal pollinators of various species belonging to the genera *Ardisia* (Myrsinaceae), *Pavetta* and *Praravinia* (Rubiaceae), *Madhuca* and *Palaquium* (Sapotaceae), along with three *Durio* species (Bombacaceae) found in the dipterocarp forests of Lambir. The readily available nectar of *Bombax ceiba* lures animals such as squirrels (Ali, 1932; Joshi *et al.*, 1995). Squirrels frequently visit many flowers in addition to *Bombax ceiba* (Khanduri and Kumar, 2017).

Exhaustion of floral resources and greater isolation of plants resulting from resource exploitation could lead to a reduction in pollinator numbers by influencing their foraging and mobility behaviors (Ghazoul and Shaanker, 2004), thus impacting the species' reproductive success (Cunningham, 2000). Honeybees have a complex pattern of action when gathering and processing these primary resources. Bee pollen analysis reveals the behavioural patterns and dietary preferences of plants. According to Khalifman (1951), the combined weight of two pollen pellets ranges from twenty to twenty-five milligrams, containing around three to four million pollen grains.

In tropical regions, there is a greater variety of pollinators, including bats and insects, which contribute to the diversity of species. This is supported by research conducted by Baker *et al.* (1983). Pollination of a plant species occurs in an environment with a high population density, rather than in isolated areas where plants and animals do not interact or rely on each other. *Apis cerana* and *Apis dorsata* play an important role in pollination within the tropical forests of the Western Ghats (Devy and Davidar, 2003; Devy and Livingstone, 2001) and in Sri Lankan ecosystems (Dayanandan *et al.*, 1990). *Zosterops*, commonly known as white-eyes, along with its related species in the Zosteropidae family, are little birds that are omnivorous and frequently visit flowers in the Oriental Region.

An estimated 87.5% of flowering plants depend on animals for pollination (Ollerton *et al.*, 2011), and animal pollinators contribute to the successful fruit and seed production in approximately 75% of key food crops (Klein *et al.*, 2007). These mutualistic relationships are, therefore, fundamental to ensuring food security and to

sustaining biodiversity among both plants and their associated animal species (Silva *et al.*, 2021a; Ollerton *et al.*, 2017; IPBES, 2016; Potts *et al.*, 2010). Natural ecosystems in tropical regions show greater reliance on animal-mediated pollination than those in temperate zones (Rech *et al.*, 2016; Ollerton *et al.*, 2011). This is partly due to the high degree of specialization in tropical plant-pollinator networks, which is driven by unique combinations of floral traits (Rosas-Guerrero *et al.*, 2014). Furthermore, tropical regions support a richer diversity of pollinators, including animals that play a more prominent role in reproductive processes of plants (Ratto *et al.*, 2018; Fleming and Muchhala, 2008). However, recent studies (Silva *et al.*, 2021b; Wenzel *et al.*, 2020) highlight a noticeable gap in research focusing on pollination ecology within tropical urban landscapes.

Plant-pollinator networks in temperate forests are nested, with key species being essential to the general integrity of the network, according to research by Ramos-Jiliberto *et al.*, (2009). With distinct evolutionary origins in the New and Old Worlds, vertebrate pollination especially that of birds and bats is widespread in tropical and subtropical locations worldwide (Fleming and Muchhala, 2008; Fleming *et al.*, 2009). Approximately 65 families comprise the over 920 bird species that pollinate plants (Cronk and Ojeda, 2008; Whelan *et al.*, 2015). Three specific groups, namely hummingbirds (Trochilidae), sunbirds (Nectariniidae), and honeyeaters (Meliphagidae), have a distinct feeding behavior since they mostly consume nectar. These birds typically form mutually beneficial connections with plants, as described by Cronk and Ojeda, (2008). Avian species, including those that play a crucial role in pollination, demonstrate a heightened sensitivity and prompt reaction to alterations in their surroundings (Whelan *et al.*, 2008). The prevalence of bird pollinators in urban contexts is greatly affected by the availability of nectar (Davis *et al.*, 2015).

A high diversity of hummingbirds was discovered in a remnant of urban forest in Brazil, underscoring the value of these habitats for the birds. The hummingbirds used these areas as a haven, feeding in the nearby urbanized area during times when floral resources were scarce (Rodrigues and Araujo, 2011). An ecosystem function that helps about 35% of the world's food production is biotic pollination (Klein *et al.*, 2007;

IPBES, 2016). Several studies have demonstrated that urbanisation has a negative impact on the reproductive performance of native plants by disrupting plant-pollinator interactions. This disruption results in poorer fruit and seed production for native plants, both in tropical and non-tropical environments (Pellissier *et al.*, 2012; Oliveira *et al.*, 2019). The detrimental effects on the reproduction of native plants can worsen when pollinators are attracted to non-native plant species that are regularly grown in urban settings, rather than native plants (Matteson and Langellotto, 2011; Helden *et al.*, 2012; Stewart *et al.*, (2018), however Nascimento *et al.* (2020) present a contrasting view. Pollination is an important ecosystem service that plays a crucial role in the sustainable development of cities. However, it is vulnerable to the adverse impacts of urbanisation (Geslin *et al.*, 2013; Harrison and Winfree, 2015; Baldock, 2020; Nicholls *et al.*, 2020; Wenzel *et al.*, 2020; Silva *et al.*, 2021b).

Global urbanisation is occurring at a fast pace, specifically affecting areas with high levels of biodiversity (Seto *et al.*, 2013). Land-use change, a significant environmental impact caused by human activities, is widely acknowledged as a primary factor contributing to the reduction of pollinators (Potts *et al.*, 2016; Millard *et al.*, 2021). These decreases are particularly worrisome due to their influence on biodiversity and the provision of ecological services. Pollinators exhibit varied responses to environmental conditions such as wind speed, humidity, and temperature, which can significantly influence both the abundance and foraging behaviour of pollinators throughout the day (Sgolastra *et al.*, 2016; Chang *et al.*, 2016). The manner in which bees land on flowers and come into touch with the stigma may be influenced by their collection of either nectar or pollen (Bakshi *et al.*, 2018b; Martins *et al.*, 2015). Therefore, environmental conditions can have an impact on both crop pollination and agricultural productivity (Tuell and Isaacs, 2010). It is crucial for sweet cherry cultivation, as the crop typically blooms during the early part of spring, which can be affected by unpredictable weather conditions (Fadón *et al.*, 2015). The flowering period usually lasts 2-5 weeks when several cultivars with early, mid, and late blooming times are mixed (Christensen, 1996).

Flowers that rely on bees for pollination have vibrant hues, reflecting light in the blue to violet range, and possess nectar guides to attract bees and obtain nectar during daylight hours (Faheem *et al.*, 2004). Flowers that are bright or light-coloured, have an appropriate scent, and have nectar guides are pollinated by moths and bats during the night (Zariman *et al.*, 2022). Flowers that have a pinkish or red color are widely recognized for their ability to attract butterflies (Abrol, 2012). The scent or aroma of the flower lures particular pollinators towards them; flowers that rely on insect pollination typically have a scent or fragrance, whilst blooms that rely on avian pollination are devoid of any odor (Johnson and Govender, 2022). In order to effectively advertise over vast distances, it is necessary to use nighttime flowering plants that emit a highly potent and widespread flowery scent. Insects are crucial for the transportation of pollen, which allows a plant species to mate with other individuals of the same species and promote gene flow within the population (van Ginkel and Flipphi, 2020). Floral characteristics such as the length of the bloom, color, odor, nectar, pollen, and other incentives have a substantial effect on pollinators, as demonstrated by Faheem *et al.*, (2004). Therefore, these factors play a crucial role in determining pollination efficiency.

Bees are highly efficient pollinators for several crops (Giannini *et al.*, 2015; IPBES, 2016). Nevertheless, bee variety has been declining, despite its significance (Potts *et al.*, 2010). Insects play a crucial role in the pollination of the majority of plant species, with bees being the primary pollinators in both tropical and non-tropical settings. They make a substantial contribution to the preservation and upkeep of natural ecosystems and offer crucial ecosystem services (Michener, 2007; Potts *et al.*, 2010; IPBES, 2016, Montoya-Pfeiffer *et al.*, 2020). The reliance of bees on floral resources at every stage of their life cycle highlights their crucial function in pollinating numerous angiosperm species. In addition to nectar, bees rely on other resources such as pollen, oil, and resin to nourish their progeny and sustain their nests (Aleixo *et al.*, 2014; Ollerton, 2017; Rocha-Filho *et al.*, 2018). The benefits of having floral resources available have been shown in tropical cities, including Costa Rica (Wojcik and McBride, 2012) and Thailand (Tangtorwongsakul *et al.*, 2018; Stewart and Waitayachart, 2020). This aligns with research undertaken in temperate areas (Ahrné *et al.*, 2009; Matteson and

Langellotto, 2010; Bates *et al.*, 2011; Hennig and Ghazoul, 2011; Pardee and Philpott, 2014; Hülsmann *et al.*, 2015).

Floral abundance and diversity play a crucial role in supporting bees from various groups and mitigating the adverse impacts commonly linked to urbanisation (Frankie *et al.*, 2013; Hülsmann *et al.*, 2015; Ayers and Rehan, 2021). Jennersten (1988), examined the effects of habitat fragmentation on *Dianthus deltoides*, a herbaceous plant in the Caryophyllaceae family that is pollinated by butterflies. The study found that locations with high fragmentation showed reduced overall variety and richness of both blooming plants and flower-visiting insects. As a result, the blooms in these fragmented areas had reduced pollinator visits and showed a decrease in the number of seeds produced. Aizen and Feinsinger (1994), conducted comparison research comparing small forest fragments with larger, more continuous forest areas. They evaluated the degrees of pollination, as well as the production of fruit and seeds, within each type of patch. Their research revealed that smaller forest patches had diminished levels of pollination, fruit set, and seed set in comparison to the larger areas.

Kunin (1993), investigated the impact of population density on pollinator visitation in wild mustard (*Brassica kaber*). The research findings indicated a substantial decline in pollinator visits when the population density was low, and plants that were placed far apart resulted in a significantly reduced production of seeds. Hackney and McGraw (2001) investigated the impact of population size on the reproductive efficacy of American ginseng (*Panax quinquefolius*). Throughout the summer blooming period, they documented the emergence of buds, the blossoming of flowers, and the development of both unripe and ripe fruit. Their findings indicated that the yield of fruit per individual plant exhibited an upward trend as the size of the flowering population rose, implying the presence of a possible Allee effect in smaller populations.

Over the past few decades, the risk of extinction has been growing for both mammal and bird pollinators. On average, 2.5 species per year have been moving closer to extinction on the IUCN Red List of Threatened Species (Regan *et al.*, 2015). The decreases in biodiversity are mostly caused by the expansion of agriculture, the

proliferation of invasive alien species, hunting activities, and the occurrence of fires (Regan *et al.*, 2015). Thapa-Magar *et al.*, 2023 investigated the impacts of canopy reduction on the interactions between bees and flowers in western North America. Compared to ecosystems with pinyon-juniper, sagebrush showed a higher level of interaction diversity. Chewing decreased the level of specialisation in the network, and bees showed a preference for various plants in each environment. The quantity of bees was greater in locations with colder temperatures and lower canopy coverage. Transitioning to sagebrush did not negatively impact the interactions between bees and flowers, indicating that it is advisable to prioritise the use of native plants for restoration purposes.

According to Whelan *et al.* (2008), around 920 bird species, including as the sunbird-loving Nectarinidae, hummingbird-loving Trochilidae, honeyeater Meliphagidae, and lory-loving Loridae, are known to pollinate plants. Birds are responsible for pollinating approximately 5.4% of the 960 cultivated plant species that rely on pollinators, as stated by Nabhan and Buchmann, (1997). In general, birds pollinate around 5% of the plant species in a given region, and this percentage increases to 10% if the region is an island, according to studies conducted by Anderson (2003); Kato and Kawakita, (2004); Bernardello *et al.*, (2006). A two-year study on *Prunus mongolica* revealed that insect-mediated pollination plays a vital role in its reproductive success, whereas wind pollination was deemed ineffective due to the rapid decline in pollen dispersal over distance. The species' floral scent and nectar acted as key attractants, drawing a total of seventeen insect pollinators, including bees, flies, and butterflies. Peak visitation occurred during full anthesis. Although *P. mongolica* exhibits a tendency toward cross-pollination, the lack of dedicated pollinators may restrict its pollination efficiency (Fang, 2007).

Chauhan (2019) reported that *Eriobotrya japonica* is primarily pollinated by insects, with *Apis mellifera* and *Xylocopa violacea* as the main floral visitors. *A. mellifera* exhibited higher visitation rates during early morning hours shortly after anthesis, contributing significantly to pollen transfer. Wind played no role in pollination. Nagaar (2015) reported that *Bauhinia vahlii* is predominantly insect-pollinated, with *Apis*

indica, *Apis dorsata*, and aphids identified as the principal pollinators. Neto (2013) found that *Bauhinia forficata* is exclusively pollinated by the hawkmoth *Manduca sexta*, whose morphology and nocturnal foraging behavior facilitate efficient pollen transfer. Despite occasional visits by large bees such as *Eulaema nigrita* and *Xylocopa brasiliatorum*, these species were not effective pollinators. The foraging behaviours, flower visits, and pollination effectiveness are influenced by attitude, temperature, light, wind, and rainfall (Akhtar *et al.*, 2018). Pollinators' foraging behaviour is affected by changes in altitude. Specifically, hummingbirds are more efficient pollinators at higher elevations compared to bees, while moths are more effective at intermediate and lower altitudes (Klomberg *et al.*, 2022).

According to McLaughlin *et al.* (2022), andrenid bees were found as the main pollinators of wild black cherry in Pennsylvania. A positive correlation was seen between the increase in andrenid abundance and higher viable seed production, especially in areas next to the forest. Andrenids transported a considerably larger amount of black cherry pollen in comparison to flies and halictid bees. The study also observed the occurrence of *Tiphia vernalis*, a parasitoid of *Popillia japonica*, consuming black cherry nectar. Mateos-Fierro *et al.* (2022) studied insect visitors in sweet cherry orchards and discovered that wild pollinators, such as solitary bees and wild queen bumblebees, exhibited behaviours conducive to successful cross-pollination, while managed pollinators, such as western honeybees and buff-tailed bumblebees, were more frequent. Over the course of two years, they recorded 1,174 pollinators belonging to 31 different species, demonstrating how a variety of pollinator populations may improve sweet cherry yields.

Gradziel (2022), achieved the successful transfer of self-compatibility and autogamy characteristics into commercially grown almond types, resulting in a decreased dependence on pollinizers and honeybee pollinators. Various sources were employed, including farmed peaches and wild almond species, to enhance the breeding material. This study emphasises the possibility of creating almond orchards with only one type of cultivar, which would make management easier and decrease the use of agrochemicals. Oldland *et al.*, (2019) studied the augmentation of European honeybees

(*Apis mellifera*) in northwest Pennsylvania to pollinate black cherries (*Prunus serotina*). Contrary to typical farming methods, their research discovered a paucity of honeybees in the upper parts of black cherry trees, indicating that efforts to increase pollination may not be effective. It is advisable to conduct additional research on alternate techniques and indigenous pollinators. In their study on *Prunus domestica* pollinators in the Kashmir valley, Dar *et al.* (2020a), identified 41 species from 5 orders, 19 families, and 28 genera that interacted with plum flowers. The main species belonged to the family Halictidae and the genus *Lasioglossum* within the order Hymenoptera. The daily level of activity reached its highest point between 10:00 and 14:00, which was directly related to the availability of floral resources. The study highlights the need of safeguarding wildflower pollinators to improve plum crop yield.

Dar *et al.* (2020b) highlighted the pivotal role of wild insect pollinators in peach (*Prunus persica*) cultivation, with foraging behaviour strongly shaped by landscape heterogeneity. Insect species from the genus *Lasioglossum*, especially *L. marginatum*, recorded the highest visitation rates, while hymenopterans, including *Xylocopa* species, emerged as the dominant pollinators. Over two years, wild bees accounted for visits to nearly 95% of available peach blossoms, reflecting their substantial contribution to effective pollination. A study in Himachal Pradesh documented 31 insect pollinator species of peach (*Prunus persica*), with Hymenoptera and Diptera as the dominant orders. *Apis cerana* and *Apis dorsata* were most abundant in Kandaghat and Gheori, while *Episyrphus balteatus* dominated in Jatoli and Summer Hill. The findings underscore the ecological importance of maintaining pollinator diversity for effective peach pollination (Dhiman, 2024). The study conducted in Jaboticabal, São Paulo, highlighted the role of key pollinators in peach (*Prunus persica*) pollination. Among the insect visitors, *Apis mellifera* was the dominant pollinator, accounting for 73% of total visits, followed by *Trigona spinipes* (17%) and *Xylocopa* species (4%). Additionally, hummingbirds were observed collecting nectar, making up 6% of floral visitors. The peak foraging activity of *A. mellifera* occurred around midday, specifically at 12:00 p.m., indicating their significant contribution to both nectar and pollen collection.

2.8 Research gaps

Although *P. cerasoides* is admired for its cultural and ornamental value, its reproductive ecology has received little scientific attention. Existing studies rarely go beyond medicinal uses or general descriptions, leaving major gaps in our understanding of its flowering, pollination, and regeneration. As a winter-flowering species, it is especially sensitive to climatic variations, yet detailed studies on how temperature, humidity, and seasonal changes influence its phenology are lacking.

Knowledge of pollination ecology is also fragmentary. The identity of effective pollinators, their visitation patterns, and their role in fruit set remain poorly understood. Similarly, little is known about fruiting success, seed viability, or the conditions that govern natural regeneration. Comparative work across tropical and temperate populations, which could reveal ecological adaptability and resilience, is virtually absent.

These gaps highlight the need for a focused study on the reproductive ecology of *P. cerasoides*. Such research will provide valuable insights into its regeneration dynamics and adaptability under changing environmental conditions.

Table 2.1 Pollen production data across different tree species

Sl. No.	Species	Family	Pollen production per tree	References
1	<i>Acer negundo</i>	Sapindaceae	15.2 to 250.1 $\times 10^9$	Molina <i>et al.</i> , (1996)
2	<i>Fraxinus angustifolia</i>	Oleaceae	11.2 to 160.7 $\times 10^9$	Molina <i>et al.</i> , (1996)
3	<i>Lannea coromandelica</i>	Anacardiaceae	1.8 to 2.8 $\times 10^9$	Molina <i>et al.</i> , (1996)
4	<i>Olea europea</i>	Oleaceae	29.1 to 108.3 $\times 10^9$	Molina <i>et al.</i> , (1996)
5	<i>Plantanus hispanica</i>	Platanaceae	114.9 to 250.6 $\times 10^9$	Molina <i>et al.</i> , (1996)
6	<i>Populus nigra</i>	Salicaceae	113.0 to 134.7 $\times 10^9$	Molina <i>et al.</i> , (1996)
7	<i>Quercus rotundifolia</i>	Fagaceae	109.4 to 633.5.7 $\times 10^9$	Molina <i>et al.</i> , (1996)
8	<i>Salix artocinerea</i>	Salicaceae	36.0 to 47.7 $\times 10^9$	Molina <i>et al.</i> , (1996)
9	<i>Ulmus minor</i>	Ulmaceae	5.0 to 8.0 $\times 10^9$	Molina <i>et al.</i> , (1996)
10	<i>Grevillea robusta</i>	Proteaceae	0.104 to 0.116 $\times 10^9$	Khanduri and Sharma, (2002b)
11	<i>Shorea robusta</i>	Dipterocarpaceae	2.0 to 3.3 $\times 10^{14}$	Bera, (1990)
12	<i>Quercus suber</i>	Fagaceae	24.046 to 55.045 $\times 10^9$	Teresa Gomez-Casero <i>et al.</i> , (2004)
13	<i>Quercus ilex</i>	Fagaceae	11,919 to 24,500 $\times 10^6$	Teresa Gomez-Casero <i>et al.</i> , (2004)
14	<i>Quercus faginea</i>	Quercus faginea	16,715 to 22,731 $\times 10^6$	Teresa Gomez-Casero <i>et al.</i> , (2004)
15	<i>Tectona grandis</i>	Lamiaceae	9.498 to 14.208 $\times 10^8$	Khanduri, (2012b)
16	<i>Cedrus deodara</i>	Pinaceae	1.9 to 21.6 $\times 10^9$	Khanduri and Sharma, (2002a)

17	<i>Pinus pinaster</i>	Pinaceae	20.9 to 32.3×10 ⁹	Molina <i>et al.</i> , (1996)
18	<i>Pinus roxburghii</i>	Pinaceae	1.2.5 to 27.3 ×10 ¹¹	Khanduri and Sharma, (2002b)
19	<i>Cunninghamia lanceolata</i>	Cupressaceae	1.31 × 10 ⁹ to 1.74 × 10 ¹⁰	Zhuowen, (2004)
20	<i>Cupressus sempervirens</i>	Cupressaceae	64.5 × 10 ⁹	Hidalgo <i>et al.</i> , (1999)
21	<i>Cupressus arizona</i>	Cupressaceae	12.3 × 10 ¹⁰	Hidalgo <i>et al.</i> , (1999)
22	<i>Cupressus macrocarpa</i>	Cupressaceae	11.4 × 10 ¹¹	Hidalgo <i>et al.</i> , (1999)
23	<i>Bombax ceiba</i>	Malvaceae	4.01× 10 ⁸ to 12.67× 10 ⁸	Khanduri <i>et al.</i> , (2015a)
24	<i>Erythrina stricta</i>	Fabaceae	8.05× 10 ⁷ to 13.91× 10 ⁷	Khanduri <i>et al.</i> , (2015a)
25	<i>Mesua ferrea</i>	Calophyllaceae	3.84× 10 ¹⁰ to 6.59× 10 ¹⁰	Khanduri <i>et al.</i> , (2015a)
26	<i>Schima wallichii</i>	Theaceae	6.90× 10 ⁷ to 16.94× 10 ⁷	Khanduri <i>et al.</i> , (2013)
27	<i>Lagerstroemia speciosa</i>	Lythraceae	5.12× 10 ⁷ to 91.87× 10 ⁷	Khanduri <i>et al.</i> , (2015a)
28	<i>Acer platanoides</i>	Sapindaceae	5.1x10 ⁹	Katz <i>et al.</i> , 2020)
29	<i>Acer rubrum</i>	Sapindaceae	2.9x10 ⁹	Katz <i>et al.</i> , 2020)
30	<i>Acer saccharinum</i>	Sapindaceae	5.7x10 ⁹	Katz <i>et al.</i> , 2020)
31	<i>Betula papyrifera</i>	Betulaceae	1.5x10 ¹⁰	Katz <i>et al.</i> , 2020)
32	<i>Gleditsia triacanthos</i>	Fabaceae	3.4x10 ¹⁰	Katz <i>et al.</i> , 2020)
33	<i>Juglans nigra</i>	Juglandaceae	1.8 x 10 ¹⁰	Katz <i>et al.</i> , 2020)
34	<i>Morus alba</i>	Moraceae	2.57x10 ¹¹	Katz <i>et al.</i> , 2020)
35	<i>Platanus acerifolia</i>	Platanaceae	8.7x10 ¹⁰	Katz <i>et al.</i> , 2020)

36	<i>Populus deltoides</i>	Salicaceae	3.5×10^{10}	Katz et al., 2020)
37	<i>Quercus palustris</i>	Fagaceae	4.6×10^{10}	Katz et al., 2020)
38	<i>Quercus rubra</i>	Fagaceae	6.3×10^{10}	Katz et al., 2020)
39	<i>Ulmus americana</i>	Ulmaceae	1.1×10^{10}	Katz et al., 2020)

CHAPTER 3

Material and Methods

3.1 Study sites:

3.1.1 Mizoram

Mizoram, located in India's northeastern corridor, covers an area of approximately 21,087 square kilometers, as reported by Singh *et al.* (2002). Geographically, the state lies between latitudes 21°30' N and 23°15' N, and longitudes 92°16' E to 93°26' E (Pachua, 1994) (Figure 3.1). The Tropic of Cancer (23°30' N latitude) passes through the Aizawl district, marking its southern edge, and crosses areas such as Champhai, Chhawrtui, Darlung, and Phuldungsei (Laldinpui and Mishra, 2019). The state is characterized by elongated north-south parallel ranges of hills with valleys in between. These ranges are composed of small hills, referred to as "Tlang" in the indigenous Mizo language, and are recognized for their distinct sharp and pointy hilltops. The average elevation of the hill ranges is around 920 meters above sea level, with the lowest elevation being 20 meters near the Karnaphuli River in Lunglei district. The highest point, located in the southeastern region at the Blue Mountain range (Phawngpui) in Lawngtlai District, rises to 2,157 meters.

Mizoram harbors numerous picturesque lakes, including Palak, Tamdil, and Rundil, that serve as habitats for aquatic plants. The state's traditional agricultural traditions encompass shifting cultivation, commonly referred to as "Jhum" farming, and household gardening. Mizoram is globally significant as it is a component of the Indo-Myanmar biodiversity hotspot (Sati, 2023). The Indo-Myanmar region, which includes Mizoram, is widely recognized for its rich biodiversity and ecological significance. Nevertheless, the state is confronted with numerous human-induced negative impacts on rich biodiversity, underscoring the significance of conservation endeavours. Mizoram, the 23rd state of India (Das, 2019) is made up of 11 administrative districts

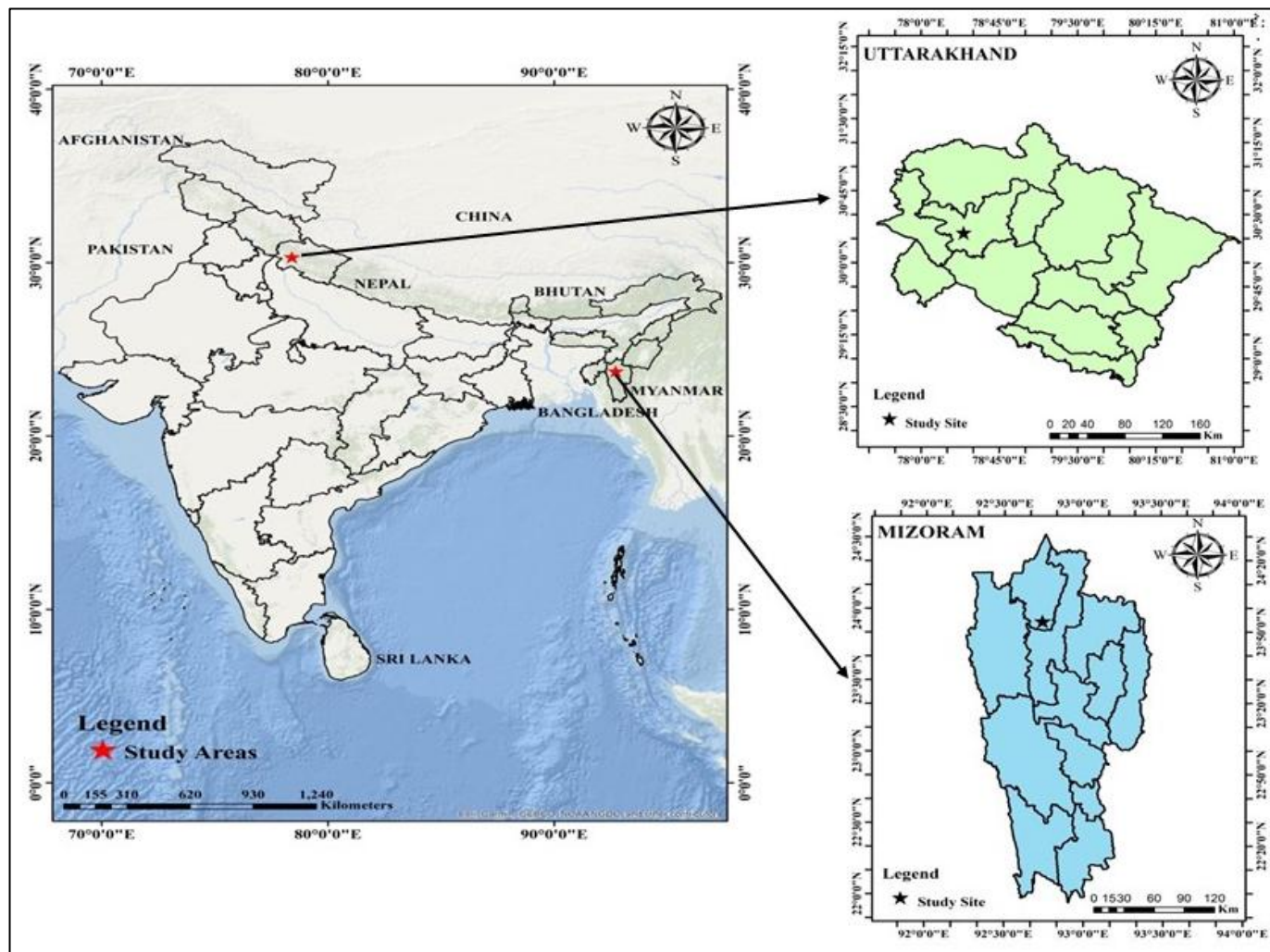


Figure 3. 1 Geographical maps of Uttarakhand and Mizoram

and shares its eastern border with Myanmar, its western border with Bangladesh, and its northern boundaries with the Indian states of Assam, Manipur, and Tripura.

The state's elevation varies from 21 to 2,157 meters a.m.s.l., and it experiences an annual precipitation range of 2,000 to 3,200 millimetres(mm). Rainfall in Mizoram is primarily governed by both the southwest and northeast monsoons, contributing to an annual precipitation range of approximately 2,000 to 3,500 mm. The monsoon season typically begins in June and continues until September, with rainfall relatively consistent throughout the state, except for the southwestern region, which tends to receive slightly more. A distinguishing feature of Mizoram's climate is the strong north-westerly thunderstorms that frequently strike during April and May, bringing intense rainfall across the hills. The region exhibits a tropical monsoon type of climate, where the upper hill regions experience cold winters and cool summers, while the lower elevations are marked by warm and humid conditions.

Temperature across the state fluctuates from about 11°C in winter to roughly 31°C during the summer and spring months. The soil has an acidic p^H, contains a high amount of organic matter, and is predominantly composed of sandy loam to loam particles. The state boasts 21 prominent hill ranges, with Phawngpui standing as the tallest, soaring 2,065 meters a.m.s.l.. Mizoram is traversed by several rivers, with those in the northern region ultimately flowing into the Barak River in Assam. In the southern part of Mizoram, rivers such as the Chhimtuipui (also known as Kolodyne), Mat, Tuichang, Tiau, and Tuipui predominantly follow a southward course. The primary forest types of Mizoram, as documented by Champion and Seth (1968) and Gogoi *et al.*, (2022), are classified based on height, rainfall, and the main species composition. These forest types include:

1. Tropical wet evergreen forest and semi-evergreen present at elevations reaching up to 900 meters above sea level.

2. Montane Subtropical Forests (900-1500 meters above mean sea level)
3. Temperate forests located at elevations above 1600 meters above mean sea level (a.m.s.l.).
4. Bamboo forests are found at elevations ranging from 40 meters to 1520 meters above mean sea level (a.m.s.l.) in tropical and subtropical regions.
5. Quercus Forests (limited regions in the eastern sections of the state)
6. Shifting Cultivation Lands

Mizoram's distinctive amalgamation of physical characteristics, rich biodiversity, and customary farming methods render it a crucial location for investigating ecological and environmental dynamics, and the repercussions of human actions on the environment. The region's abundant natural heritage and high conservation value underscore the significance of conserving the varied ecosystems. Aizawl district lies in northern Mizoram and is geographically positioned within the latitudinal range of 23°18'17.78" to 24°25'16.04" N and the longitudinal span of 92°37'03.27" to 93°11'45.69" E. Covering an expanse of 357.31 square kilometers, the district constitutes approximately 16.96% of Mizoram's landmass. The climograph for the study region in Mizoram indicates a pronounced seasonal rainfall trend, with peak precipitation typically recorded in the monsoon period spanning June to August for the years 2020, 2021, and 2022. Notably, June 2020 recorded the highest peak in rainfall, exceeding 500 mm. Significant rainfall was also observed during July 2021 and July 2022. Rainfall remains very low during the winter months (November to February). Humidity levels are generally high throughout the year, peaking during the monsoon season. Maximum and minimum temperatures rise gradually toward the pre-monsoon period (April–May) and decline during the cooler months (December–January) (Figure 3.2)

The district is adjacent to Champhai District and Manipur state to the east and is separated from the Mamit District and the Kolasib District by its western boundary. Assam state is situated to the north, while the Serchhip District of Mizoram forms its southern boundary. The unique topography and borders of the Aizawl district add to its originality within the overall environment of the state.

3.1.2 Uttarakhand

Uttarakhand, located in the magnificent Himalayas, is a state in northern India renowned for its awe-inspiring natural landscapes, profound spiritual importance, and abundant cultural legacy. The state is located in the Himalayas and is commonly known as the "Dev Bhumi" or "Land of the Gods" (Bhatt, 2024; Das, 2013) since it has many religious sites and places of pilgrimage. Uttarakhand, India's 27th state, lies geographically between latitudes 28°44' and 31°28' N and longitudes 77°35' and 81°01' E. It was officially established on November 9, 2000, following its bifurcation from the state of Uttar Pradesh. Spanning 53,483 square kilometers, the region is primarily mountainous, featuring extensive snow-covered areas and rugged, steep terrains (Figure 3.1).

It shares its northern boundary with Tibet and is bordered by Nepal to the east, while Himachal Pradesh and Uttar Pradesh lie to the west and south, respectively. Uttarakhand is administratively divided into two regions, comprising 13 districts, 78 tehsils, and 95 development blocks. The Garhwal region includes the districts of Dehradun, Haridwar, Pauri, Rudrapur, Tehri, Chamoli, and Uttarkashi, whereas the Kumaon region consists of Bageshwar, Champawat, Almora, Nainital, Pithoragarh, and Udham Singh Nagar.

The area is a paradise for individuals who appreciate nature and enjoy seeking out thrilling experiences. It features captivating hill stations such as Mussoorie, Nainital, and Ranikhet, each offering stunning vistas of the Himalayas and serene lakes. Uttarakhand is home to revered pilgrimage centers including Char Dham (comprising Gangotri, Yamunotri, Kedarnath and Badrinath) along with Rishikesh, Haridwar, and Hemkund Sahib. These holy sites draw countless pilgrims and spiritual seekers throughout the year.

The area is a paradise for individuals who appreciate nature and enjoy seeking out thrilling experiences. It features captivating hill stations like Nainital, Mussoorie, and Ranikhet, each providing breathtaking views of the Himalayan mountains and peaceful lakes. Uttarakhand is home to esteemed pilgrimage destinations such as the Char Dham (Yamunotri, Gangotri, Kedarnath, and Badrinath), Haridwar, Rishikesh, and Hemkund Sahib. These sacred locations attract a large number of devotees and others seeking spiritual comfort.

Uttarakhand falls within the 2B (Western Himalaya) and 7B (Shiwalik Hills) biogeographic regions, encompassing the Garhwal and Kumaon divisions. The state spans 53,483 square kilometers, which represents approximately 1.6% of India's total geographical area, with 46,035 square kilometers comprising mountainous landscapes. Forests are the state's most valuable natural resource, known for their rich biological diversity. In terms of the percentage of officially recorded forest cover, Uttarakhand ranks sixth among Indian states. The landscape of the state features significant variation, ranging from high-altitude alpine regions to areas with tropical and subtropical climates. Roughly 3.47 million hectares of its land area is covered by forests, amounting to approximately 71% of its total geographical expanse. The range of forest types includes Tropical Moist Forests (500–1000 m elevation), Subtropical Pine Forests (1000–2000 m), Himalayan Moist Temperate Forests (2000–3000 m), Sub-Alpine Forests (3400–4000 m), and Alpine Forests found at elevations above 4000 m.

Uttarakhand is typically divided into three main physical regions: the Himalayas, the Shiwalik ranges, and the Tarai plains. The state experiences mostly mild weather, with warmer, tropical conditions common in the lowland areas. The average yearly rainfall is around 1550 millimetres. Uttarakhand is distinguished by its rich plant and vegetation diversity, which encompasses numerous orchid species, economically important and horticultural plants such as bamboo, as well as wild genetic resources of certain cultivated crops. The state's rich flora is largely attributed to its extensive geographical range, varied terrain, and fluctuating climatic conditions. Its Himalayan landscapes are home to numerous wetlands and major perennial rivers, such as the

Alaknanda, Bhagirathi, Ganga, Yamuna, Ramganga, Sharda, Saryu, Nayar, Kosi, and their tributaries. These wetlands support exceptional animal biodiversity, extending from single-celled organisms to mammals, and are considered highly productive yet ecologically sensitive systems. They provide vital year-round roosting, nesting, and shelter for both resident and migratory birds.

Uttarakhand hosts an exceptionally diverse range of fauna, underscoring its vast ecological richness. Since its establishment, surveys have identified 3,748 faunal species within the state. This figure encompasses 451 distinct species and subspecies, two taxa newly described to science, and 22 species newly reported from India. Among these, ten are endemic to the country. The recorded fauna includes 1,060 vertebrate species, 2,020 insect invertebrates, and 4,346 invertebrate species from other groups. Due to its remarkable biodiversity, the state harbors a wide array of rare and endangered species of medicinal and aromatic plants. In recognition of the significant potential of these biological resources, the state government has officially designated Uttarakhand as a “Herbal State.” Furthermore, the state's enduring natural beauty, deep-rooted cultural heritage, and emphasis on sustainable development contribute to its appeal as a destination for individuals seeking serenity, ecological richness, and spiritual experience.

The study was conducted in Ranichauri, Tehri Garhwal, which lies at approximately 30°18' north latitude and 78°24' east longitude, with an elevation range of 1,600 to 2,192 meters above mean sea level. The study site Ranichauri, Tehri Garhwal is situated between 30°18'N latitude and 78°24'E longitude, with an elevation ranging from 1,600 to 2,192 meters above sea level. The soil in this region is predominantly silty clay loam with a characteristic brownish-black hue and is classified under the orthents subgroup of Entisols, exhibiting a pH between 5.3 and 5.6 (Khanduri *et al.*, 2019). Dominant tree species present in the area include *Cedrus deodara*, *Quercus leucotrichophora*, *Lyonia ovalifolia*, *Pinus roxburghii*, *Prunus cerasoides*, *Pinus wallichiana*, *Rhododendron arboreum*, *Myrica esculenta* and *Pyrus pashia*. Situated in the mid-elevation zone of the Himalayan region, the site is characterized by a moist temperate climate, marked by cold winters. Snowfall generally occurs between mid-

December and mid-January. Climatic data indicate a highly seasonal rainfall pattern, with precipitation peaking during the monsoon season, particularly in July and August. Notably, the months of July 2021 and July 2022 recorded the highest rainfall, each exceeding 350 mm. In contrast, the winter months (November to February) consistently show minimal or negligible rainfall. Humidity follows a similar pattern, increasing sharply during the monsoon, while maximum and minimum temperatures peak during the pre-monsoon summer months (April–June) and decline during winter (December–January) (Figure 3.2).

3.1.3 Climate and weather of the study sites

Mizoram (2019)

In 2019, Mizoram experienced varying weather patterns across the months. The rainfall ranged from 0 mm in January to a peak of 539 mm in July. The humidity levels fluctuated, with the lowest recorded at 65.8% in December and the highest at 92.8% in June. The maximum temperature in Mizoram ranged from 11.5°C in December to 34.0°C in April. The minimum temperature ranged from as low as 0.1°C in January to a peak of 24.8°C in June (Table 3.1).

Uttarakhand (2019):

In 2019, Uttarakhand showed distinct seasonal changes. Rainfall in Uttarakhand ranged from 98.6 mm in January to 175.6 mm in July. Humidity levels were highest in August at 88.0% and lowest in May at 43.9%. The maximum temperature in Uttarakhand varied from 10.5°C in January to 27.7°C in June. Minimum temperatures fluctuated between 0.1°C in January and reached up to 15.4°C in August (Table 3.1).

Mizoram 2020

Mizoram experienced a distinct seasonal pattern in 2020, with heavy rainfall concentrated from May to October, peaking in October (385 mm) and May (290 mm), indicating a strong monsoon influence. The humidity remained high throughout the

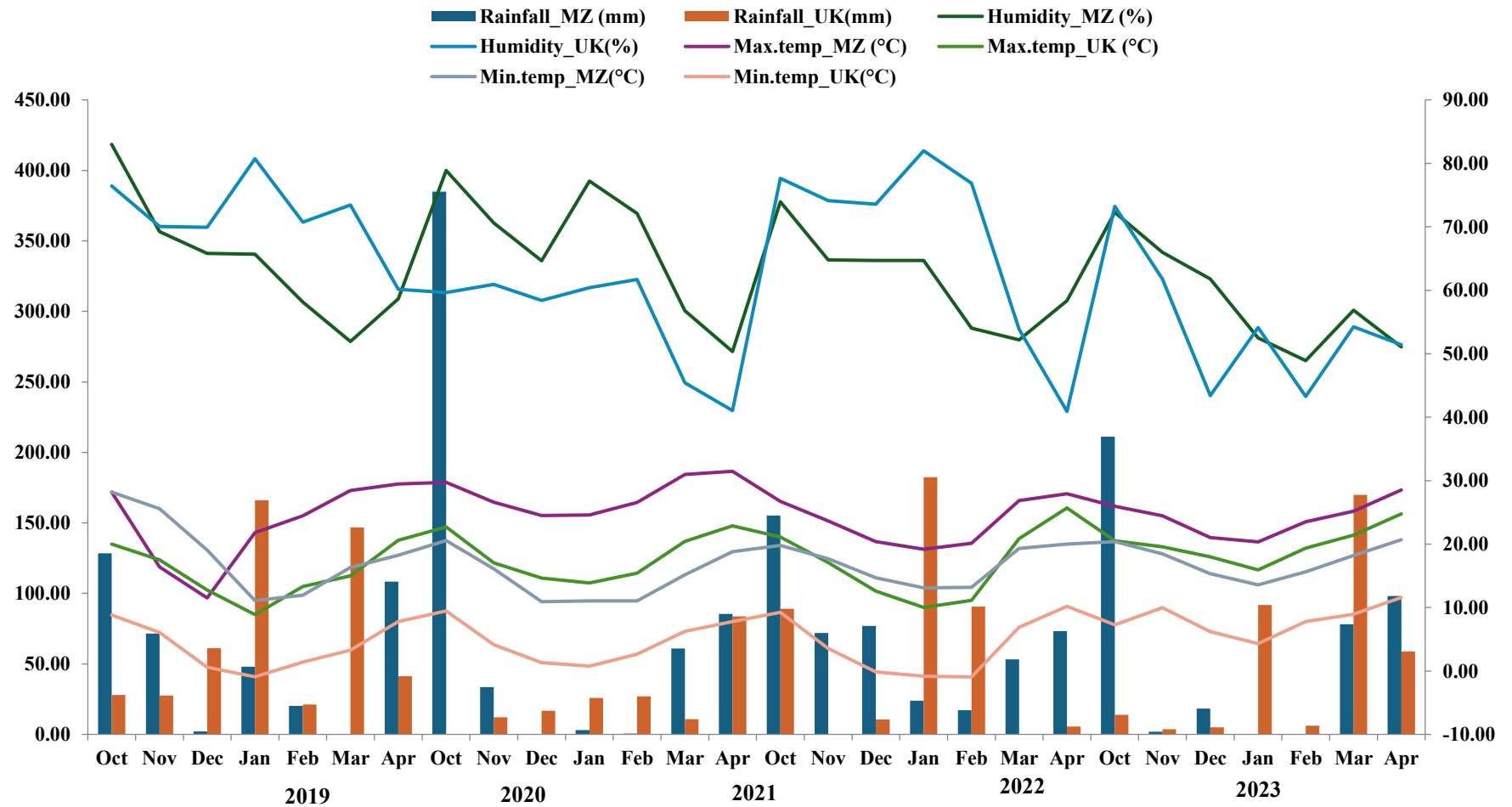


Figure 3. 2 Monthly mean climatic variable (rainfall, maximum and minimum temperature, and humidity) at two ecologically distinct study sites of Uttarakhand (UK) and Mizoram (MZ) during the study period (2019-2023)

year, particularly during the monsoon months (June–September), reaching its peak in July (83.1%). Temperatures were consistently warm, with maximum temperatures hovering around 28–30°C from April to October and minimum temperatures rarely dropping below 10°C, even in winter. The driest months were March and December, with no recorded rainfall, while November and February also saw relatively low precipitation. Mizoram’s climate was tropical, with a pronounced wet season and mild winters (Table 3.2).

Uttarakhand 2020

Uttarakhand in 2020 exhibited a temperate maritime climate, with rainfall distributed across the year but peaking in summer (July–August), notably in August (308.9 mm). Winter months (January–March) also saw significant rainfall, particularly in January (166.1 mm) and March (146.8 mm). Humidity was highest during the summer (July–September), exceeding 85% in August, while October and December were comparatively drier. Temperatures followed a typical seasonal cycle, with maximum temperatures reaching 23–24°C in summer (June–August) and dropping to 8–15°C in winter. Minimum temperatures often fell near or below freezing in winter (e.g., January: -0.9°C) but stayed mild in summer (13–16°C). The Uttarakhand’s climate remained variable, with no extreme dry spells but a wetter summer and cooler winters (Table 3.2).

Mizoram (2021)

In 2021, Mizoram experienced a predominantly humid and warm climate with substantial rainfall concentrated in the monsoon months. Rainfall levels were highest in July (360.3 mm), August (353.5 mm), and June (336.1 mm), reflecting the strong influence of the southwest monsoon. The driest months were February (0.5 mm) and January (3 mm), indicating a pronounced dry winter season. Humidity in Mizoram remained high throughout the year, peaking at 77.2% in January and reaching a low of 50.3% in April. Temperature patterns were typical of a subtropical region, with

maximum temperatures ranging from 20.4°C in December to 31.5°C in both April and May. Minimum temperatures varied moderately, from a low of 11.0°C in January and February to a high of 19.8°C in both May and October. Overall, Mizoram's 2019 climate was characterized by mild winters, hot pre-monsoon months, and a long, wet monsoon season accompanied by consistently high humidity (Table 3.3).

Uttarakhand (2021)

Uttarakhand's climate in 2021 showed a marked seasonal contrast, reflecting its location in the temperate Himalayan region. Rainfall peaked in July at 349.2 mm and was also notably high in May (208.1 mm) and September (213.9 mm), indicating the dominance of the monsoon season. The state experienced little to no rainfall in November (0.0 mm), December (10.6 mm), and March (10.8 mm), showing distinct dry periods. Humidity levels followed a seasonal trend, reaching their highest in August at 91.7% and lowest in April at 41.1%, suggesting a drier pre-monsoon period. Maximum temperatures ranged from 12.6°C in December to 23.4°C in both June and July, indicating moderate summer warmth. Minimum temperatures varied significantly, from a freezing -0.2°C in December to a milder 14.9°C in July. These figures reflect the strong seasonality of Uttarakhand's climate, with cold winters, a warm and wet summer, and a clear monsoonal influence during mid-year (Table 3.3).

Mizoram (2022)

In 2022, Mizoram experienced a typical humid subtropical climate with heavy rainfall primarily concentrated during the monsoon months. The year's highest rainfall was recorded in July (460.2 mm), followed by June (355.3 mm) and May (327.8 mm), indicating the strong influence of the southwest monsoon beginning in late spring. November was the driest month, with only 2 mm of rainfall, while February and January also remained relatively dry at 17.2 mm and 23.9 mm, respectively. Humidity levels were consistently high, peaking in June (78.8%), July (76.7%), and September (76.0%), and reaching their lowest in March (52.2%), aligning with the dry pre-monsoon period. Maximum temperatures varied from 19.2°C in January to a high

of 31.5°C in April. with warm conditions prevailing from spring through early autumn. Minimum temperatures remained mild throughout the year, ranging from 13.1°C in January to a high of 21.4°C in September, with no extreme cold observed. Overall, Mizoram's 2022 climate was warm, consistently humid, and defined by a clear and intense monsoon season between May and September (Table 3.4).

Uttarakhand (2022)

In 2022, Uttarakhand experienced a highly seasonal climate, heavily influenced by its mountainous terrain. Rainfall was most abundant in the peak monsoon period, with rainfall amounts of 351.6 mm in July and 298 mm in August, while the early months also saw significant winter precipitation, especially in January (182.5 mm). In contrast, March recorded no rainfall, and November and December remained very dry, with 3.65 mm and 5.09 mm, respectively. Humidity levels showed a strong correlation with rainfall patterns, rising to 90.6% in August and 90.1% in July and dropping to 40.9% in April, which marked the driest part of the year. The maximum temperature rose gradually from 10.0°C in January to 26.5°C in June before slightly declining during the rainy season. Minimum temperatures ranged from -0.9°C in February, reflecting cold winter conditions, to 14.1°C in July, indicating comfortable summer nights. Overall, Uttarakhand's 2022 climate was marked by cold, wet winters, a dry spring, and a humid, rainy monsoon season, followed by a cool and dry post-monsoon transition. The strong seasonal shifts in both temperature and rainfall highlight the temperate nature of the region (Table 3.4).

3.1.2 Climate data

Climatic data, including monthly records of temperature and precipitation for the years 2019 to 2022, were obtained from the College of Forestry, Ranichauri, Tehri Garhwal, under the ICAR-All India Coordinated Research Project on Agrometeorology (AICRPAM), and the State Meteorological Centre, Directorate of Science and Technology, Government of Mizoram. These data were used to analyze seasonal and annual climatic trends relevant to the study area.

Table 3. 1 Rainfall, humidity and temperature of study area (2019)

Months	Rainfall (mm)		Humidity (%)		Max.temp (°C)		Min.temp (°C)	
	Mizoram	UK	Mizoram	UK	Mizoram	UK	Mizoram	UK
January	0	98.6	82.5	71.0	27.2	10.5	13.1	0.1
February	42	136.8	82.0	77.2	29.7	11.3	14.3	1.5
March	37	40.9	79.5	62.9	28.5	15.9	15.8	4.4
April	104	22.5	88.0	57.8	34.0	22.4	17.1	10.0
May	190.7	21.3	85.9	43.9	32.2	26.0	18.0	12.1
June	154	39.5	92.8	56.6	24.0	27.7	24.8	14.3
July	539	175.6	91.2	87.7	27.2	23.4	21.1	15.3
August	260	172.2	90.1	88.0	29.5	23.4	20.9	15.4
September	181	139.1	91.3	87.1	26.0	22.6	15.9	14.1
October	128.4	27.9	83.0	76.5	28.2	20.0	28.2	8.8
November	71.5	27.5	69.3	70.1	16.4	17.5	25.6	6.1
December	2.2	61.1	65.8	69.9	11.5	12.8	19.0	0.6

Table 3. 2 Rainfall, humidity and temperature of study area (2020)

Months	Rainfall (mm)		Humidity (%)		Max. temp (°C)		Min.temp (°C)	
	Mizoram	UK	Mizoram	UK	Mizoram	UK	Mizoram	UK
January	48.1	166.1	65.7	80.7	21.8	8.9	11.1	-0.9
February	20.2	21.2	58.1	70.7	24.4	13.3	11.9	1.4
March	0.0	146.8	51.9	73.4	28.4	15.0	16.3	3.3
April	108.3	41.2	58.6	60.2	29.5	20.6	18.3	7.8
May	290.0	55.0	73.6	62.6	28.0	23.4	19.9	10.6
June	218.3	122.4	82.6	79.8	28.4	23.5	20.8	13.8
July	243.1	255.9	83.1	86.2	28.0	23.7	20.8	15.0
August	156.9	308.9	78.6	88.7	29.5	23.5	21.3	15.7
September	238.1	18.6	77.1	84.3	28.8	23.7	20.3	14.1
October	385.0	0.0	78.9	59.6	29.7	22.7	20.6	9.4
November	33.5	12.1	70.6	60.9	26.6	17.0	16.1	4.1
December	0.0	16.8	64.6	58.4	24.5	14.6	10.9	1.3

Table 3. 3 Rainfall, humidity and temperature of study area (2021)

Months	Rainfall (mm)		Humidity (%)		Max.temp (°C)		Min.temp (°C)	
	Mizoram	UK	Mizoram	UK	Mizoram	UK	Mizoram	UK
January	3	25.9	77.2	60.4	24.6	13.9	11.0	0.8
February	0.5	26.9	72.1	61.7	26.6	15.4	11.0	2.7
March	61	10.8	56.8	45.4	31.0	20.4	15.2	6.2
April	85.5	83.7	50.3	41.1	31.5	22.9	18.8	7.8
May	164.2	208.1	56.2	67.2	31.5	22.6	19.8	9.8
June	336.1	163.4	65.1	80.0	29.4	23.4	18.4	12.6
July	360.3	349.2	64.1	91.3	29.1	23.4	18.1	14.9
August	353.5	189.5	64.5	91.7	28.8	23.0	17.9	14.5
September	249.3	213.9	60.7	90.1	30.4	22.5	17.6	13.1
October	155.2	89.1	74.0	77.6	26.7	21.1	19.8	9.2
November	72	0.0	64.8	74.1	23.6	17.1	17.7	3.5
December	77	10.6	64.7	73.5	20.4	12.6	14.7	-0.2

Table 3. 4 Rainfall, humidity and temperature of study area (2022)

Months	Rainfall (mm)		Humidity (%)		Max.temp (°C)		Min.temp (°C)	
	Mizoram	UK	Mizoram	UK	Mizoram	UK	Mizoram	UK
January	23.9	182.5	64.7	82.0	19.2	10.0	13.1	-0.8
February	17.2	90.6	54.0	76.9	20.1	11.1	13.2	-0.9
March	53.3	0	52.2	53.9	26.8	20.8	19.3	6.9
April	73.2	5.6	58.4	40.9	27.9	25.7	20.0	10.2
May	327.8	67.8	75.2	64.4	26.8	24.7	20.3	10.7
June	355.3	110.1	78.8	63.0	26.6	26.5	20.3	13.2
July	460.2	351.6	76.7	90.1	27.2	24.0	21.3	14.1
August	277.8	298	73.5	90.6	27.1	24.2	21.2	13.9
September	195	214.8	76.0	88.6	26.7	22.3	21.4	12.2
October	211.1	13.8	72.3	73.2	25.9	20.5	20.4	7.3
November	2	3.65	66.0	61.8	24.4	19.5	18.5	10.0
December	18.3	5.09	61.8	43.4	21.0	18.0	15.3	6.2

3.2 Methodology

3.2.1 Reproductive phenology

Phenological records of the flowers were collected from 10 individuals that were randomly selected in forest locations at Ranichauri, Uttarakhand (30.18° N, 78.24° E) and Aizawl, Mizoram (23.73° N, 92.72° E). The selected individuals in both locations had almost similar heights and diameters. Seven variables were recorded during the study period: (i) Onset refers to the date when the first flower in anthesis appeared. (ii) Duration refers to the period between the date of the first flower and the date of the last bloom. (iii) Peak of flowering is determined by calculating the average census dates of individuals' flowers, with each census date weighted by the number of flowers during that period, as explained by Bishop and Schemske, (1998). The dates of the initial and last flower sightings were recorded to measure the length of the blossoming period. The peak flowering occurred when half of the tree's flowers were in bloom. (iv) Mean flowering amplitude refers to the average number of flowers produced within a specific time period, as defined by Newstrom *et al.*, 1994. (v) Flowering synchrony refers to the degree of overlap in flowering among individuals, as described by Augspurger(1983a). (vi) Fruit setting refers to the development and retention of fruits. (vii) Fruit drop refers to the shedding of fruits. The aforementioned observations were supposed to be conducted throughout a consecutive two-year period spanning from 2019 to 2021. As a result of the COVID-19 pandemic, I was unable to conduct the experiment between the years 2020 and early month of 2021. This interruption had an impact on the gathering of data for specific variables and the overall schedule of the study. The data collection was resumed from 2021 onwards. All seven variables related to the timing of flowering were evaluated for both individual plants and the entire population, with the exception of synchronisation. The chosen individual trees were labelled with paint and subsequently observed for the following year's sampling.

3.2.2 Floral development and anthesis pattern and anther dehiscence

A comprehensive investigation was conducted to examine the entire developmental behaviour of *P. cerasoides* flowers, starting from bud initiation till they reached maturity in both study site. This study utilised a sample size of 50 flowers, which were randomly selected among selected individual trees in both study sites. Field observations were made during the flowering season to record the timing of anthesis, and anther dehiscence with respect to climatic variables in each study sites. To achieve this objective, blooms from ten distinct tree individuals were marked and their anthers were observed at two hours intervals i.e. 06:00–08:00, 08:01–10:00, 10:01–12:00, 12:01–14:00, 14:01–16:00, and 16:01–18:00. Each observation included assessing the opened anthers, mode of anther dehiscence and recorded respective weather conditions. The start and end dates of flowering were documented to determine the length of the flowering season. Peak flowering was identified as the time when approximately 50% of the plant's flowers were open at both study locations.

3.2.3 Stigma receptivity, mating system, and fruit set

Stigma receptivity was evaluated using a peroxidase-based hydrogen peroxide test as described by Dafni (1992). This method is based on the enzymatic reaction between peroxidase enzymes on the stigma and hydrogen peroxide (H_2O_2), producing oxygen bubbles as an indicator of receptivity. The hydrogen peroxide solution (3%) was applied directly to the stigma surface of flowers at different developmental stages using a dropper. After the reaction was observed, the flowers were clipped. The presence and intensity of bubbling indicated the level of receptivity (Zeisler, 1938; Khanduri *et al.*, 2013; Li *et al.*, 2018; Khanduri *et al.*, 2019; Wani *et al.*, 2022; Rashid *et al.*, 2023).

Observations were recorded at two-hour intervals beginning at 06:00, continuing until 18:00 (i.e., 06:00–08:00, 08:01–10:00, 10:01–12:00, 12:01–14:00, 14:01–16:00, and 16:01–18:00.). Each time block included ten replicates to assess diurnal variation in

stigma receptivity. The mating system was examined through a series of experimental treatments: (i) natural pollination, where flowers were left exposed without any manipulation; (ii) autonomous self-pollination, in which floral buds were enclosed for the entire flowering period to prevent external pollen transfer; (iii) hand self-pollination, where bagged flowers were artificially pollinated using their own pollen; (iv) open cross-pollination, involving emasculation of anthers while allowing the stigmas to be exposed for natural cross-pollen deposition; (v) hand cross-pollination, where emasculated and bagged flowers were pollinated using pollen sourced from a different plant; and (vi) apomixis testing, where both the anthers and stigma were removed from the floral buds. Fruit set outcomes were compared between hand-self and hand-cross pollination treatments, as well as between open-pollinated and hand-cross treatments. To estimate self-incompatibility, a ratio was calculated by dividing the average fruit set from self-pollination by that from cross-pollination, following the method of Lloyd and Schoen (1992). The selfing rate was determined using the methodology outlined by Charlesworth and Charlesworth, (1987). The aforesaid mating system evaluation was conducted at both study sites.

3.2.4 Pollinator availability and frequency

During the blooming period, pollinator visitation frequency was recorded on ten randomly selected individual trees of almost the same diameter and height at both study sites. Observations were conducted on five main flowering branches per tree, ensuring consistent sampling effort across all individuals. The study was done over a period of 15 days, namely during the peak flowering season. Data was collected at each site, starting from the first bloom of the flower on ten selected plants. A data sheet was created to gather the necessary data in accordance with its specific requirements. The data set documented the number of visits; the flowers visited, the frequency of visits, contact with the reproductive parts, and interactions with other visitors.

The population was observed from morning 0600 h to evening 1800 h. Each block was observed at intervals of 2 h, specifically between 06:00–08:00, 08:01–10:00, 10:01–

12:00, 12:01–14:00, 14:01–16:00, and 16:01–18:00. The frequency of pollinators was quantified as the number of visits/flower/ two hours.

The primary pollinators observed during the field study were butterflies, moths, bees, and insects. Using a high-resolution camera, high-resolution photos of pollinators were captured during the field observation. The butterfly specimens captured in the images were identified using a range of field guides and reference works. These included *Butterflies of India* (Antram, 1924), *The Book of Indian Butterflies* (Kehimkar, 2008), and *The Dictionary of Butterflies and Moths in Colour* (Laithwaite *et al.*, 1975). Additional identification support came from region-specific works such as *Butterflies and Moths of Pakke Tiger Reserve* (Sondhi and Kunte, 2014), its second edition (Sondhi and Kunte, 2018), and *Butterflies of the Garo Hills* (Sondhi *et al.*, 2013).

3.2.5 Pollen production

The pollen productivity was calculated according to the methodology described by Molina *et al.*, (1996). The number of pollen grains per anther was estimated by counting the total pollen from ten flower buds ($n = 10$) collected per individual tree. Since ten trees were sampled from each site, the total number of anthers assessed per site was 100 ($n = 100$). This allowed us to estimate the production of pollen grains per flower and per plant. A single anther was taken from each bloom and placed onto a glass slide. The anther was then combined with safranin stain. The safranin stain's pinkish hue is absorbed by the pollen, rendering them readily identifiable and apparent when observed under a stereoscopic microscope. A needle was used to gently crush the anther, and sharp forceps were used to remove the outer covering of the anther. Subsequently, the components were meticulously blended and evenly distributed onto the glass slide. Once the glass slide had fully dried, it was affixed with DPX and allowed to dry out once more. Uniform little square boxes were sketched on the reverse side of the glass slide. Each minuscule square compartment was examined using a stereoscopic microscope, and the number of pollen grains in each compartment was visually tallied.

The pollen grain production per plant is determined by multiplying the average amount of pollen grains per anther by the average number of stamens per flower, and then further multiplying it by the total number of blossoms produced per plant. The quantification of fruit production involved the meticulous enumeration of every individual fruit that had developed in both the main branches and smaller branches of a randomly chosen sample of trees. The pollen-ovule ratio was determined by dividing the quantity of pollen grains per flower by the estimated number of ovules per flower, following the methodology outlined by Cruden, (1977).

3.2.6 Pollen viability

Ten separate individual trees were selected for investigation, and flower samples were gathered from each tree during anthesis from both study sites during the flowering period. The plants were spaced 100 metres apart from one another. For the purpose of assessing pollen viability, we chose both recently bloomed flowers and flowers that had not yet opened (just prior to blooming). A 0.5% solution of 2,3,5-triphenyl tetrazolium chloride (TTC) in sucrose was prepared as a staining medium. Pollen grains were carefully transferred onto a cavity slide containing the TTC solution, and a cover slip was gently placed over them to limit light exposure. The slides were incubated in a dark room for 1 to 2 hours. Following incubation, observations were made under a light microscope at 5× and 10× magnifications. Pollen grains exhibiting red staining were considered viable (Shivanna and Rangaswamy, 2012).

The percentage of viable pollen grains was calculated using the following formula:

$$\text{Pollen viability (\%)} = (\text{Number of viable pollen grains} / \text{Total number of pollen grains observed}) \times 100$$

3.2.7 Effect of growth regulators on pollen germination

Pollen germination was studied under in vitro conditions using the standard medium formulated by Brewbaker and Kwack (1963). The impact of sucrose was assessed by supplementing the medium with concentrations of 5% and 10%, while distilled water served as the control. To evaluate the influence of plant growth regulators, indole-3-

acetic acid (IAA), indole-3-butyric acid (IBA), gibberellic acid (GA₃), and kinetin were added to the base medium at concentrations of 100, 200, and 300 ppm.

The experiment was conducted using a randomized complete block design with five replications, with blocks distributed across different time periods (Tuinstra and Wedel, 2000). Pollen grains collected from freshly opened anthers were gently transferred onto the germination medium on cavity slides using a fine needle. These slides were then kept at room temperature for incubation and examined under a light microscope after 24, 48, and 72 hours. In accordance with the criteria described by Tuinstra and Wedel (2000), a pollen grain was considered germinated when the pollen tube reached a length equal to or greater than the grain's diameter. Each slide was assessed across ten microscopic fields to evaluate pollen germination. The counts of both germinated and ungerminated pollen grains were recorded for every field, and the germination rate was calculated as a percentage. Statistical analysis was performed using Microsoft Excel 2016 to evaluate the effects of sucrose levels, hormone treatments, incubation time, and plant species on in vitro pollen germination.

3.2.8 Statistical analysis

Statistical evaluation of the data obtained from fieldwork and laboratory experiments was carried out using MS Excel 2019 and IBM SPSS Statistics 25. Descriptive statistics such as the mean, standard deviation, and standard error were computed. To explore associations between floral traits, climatic factors (temperature and humidity), and pollinator visitation, Pearson's correlation coefficient was applied. The effects of year and population on variables such as flower count, anther number, pollen production per plant, and fruit set were assessed through analysis of variance (ANOVA). Additionally, the influence of plant species on these reproductive parameters was examined. The study further analyzed the effects of distilled water and sucrose concentrations (5% and 10%) across different time intervals, as well as the role of growth regulators, their dosages, duration, and species type on germination and fruit set. All statistical tests were conducted using IBM SPSS Statistics version 26. A geographic map of the study area was generated using ArcGIS version 10.8.2.

CHAPTER 4

Results

4.1 Floral biology: anthesis, stigma receptivity and anther dehiscence of *P. cerasoides* (Mizoram).

The species *P. cerasoides* is recognized as a medium-sized deciduous tree. The mean height of the plant is 8.815 ± 5.05 metres, and the mean girth of the plant is 77.8 ± 0.67 cm. The leaves of this plant exhibit double serration, an oval shape, with acuminate tip, and a glabrous surface. The bark of *P. cerasoides* exhibits a characteristic peeling behavior where thin, glossy horizontal stripes are shed, revealing a lustrous copper hue. The flower exhibits a length of 21.92 ± 1.48 mm and a width of 29.67 ± 1.88 mm and bisexual. The calyx exhibits a green hue and consists of five sepals, measuring 10.59 ± 1.56 mm in length and 4.82 ± 0.80 mm in width. The mean number of stamens per flower was determined to be 34.56 ± 1.78 and 33.42 ± 1.52 for the years 2019 and 2020, respectively. The length of the stamens is recorded as 11.14 ± 1.38 mm, while the anthers are described as having a yellowish colour. Additionally, the stigma is measured to be 14.71 ± 1.46 mm in length. The total count of stigma is one; nevertheless, it was noted that in the field of study under investigation, the presence of two to three stigmas was infrequent (Figure 4.1). The filament originated as a cluster around the base of the flower adjacent to the calyx wall but began to diverge towards the distal end of the calyx. On the research site, it was noticed that the majority of flowers exhibited five petals, while occasional instances of flowers with six petals or seven were also documented (Figure 4.2). *P. cerasoides* possesses a solitary ovule (Figure 4.3). Anthesis began, on average, 8 to 10 days following floral bud initiation, according to observations made throughout the study period (Figure 4.4). The flower's opening, known as the anthesis, showed a diurnal rhythm between 0600 and 1800 hours. Despite the fact that anthesis happened all throughout the day, the flower's average maximum opening was noted between 06:00 and 08:00, coinciding with the period of maximum recorded temperature then 08:00 to 01:00, and the least amount of opening was seen between 1600 and 1800 hours.



Figure 4. 1 Variation in stigma numbers in *P. cerasoides* (Mizoram). A. Two numbers of stigmas B. Three numbers of stigmas C. One stigma



Figure 4. 2 Variation in the number of petals in *P. cerasoides* (Mizoram)



Figure 4. 3 Ovule under stereo-zoom microscope



Figure 4. 4 Pattern of anthesis in Mizoram

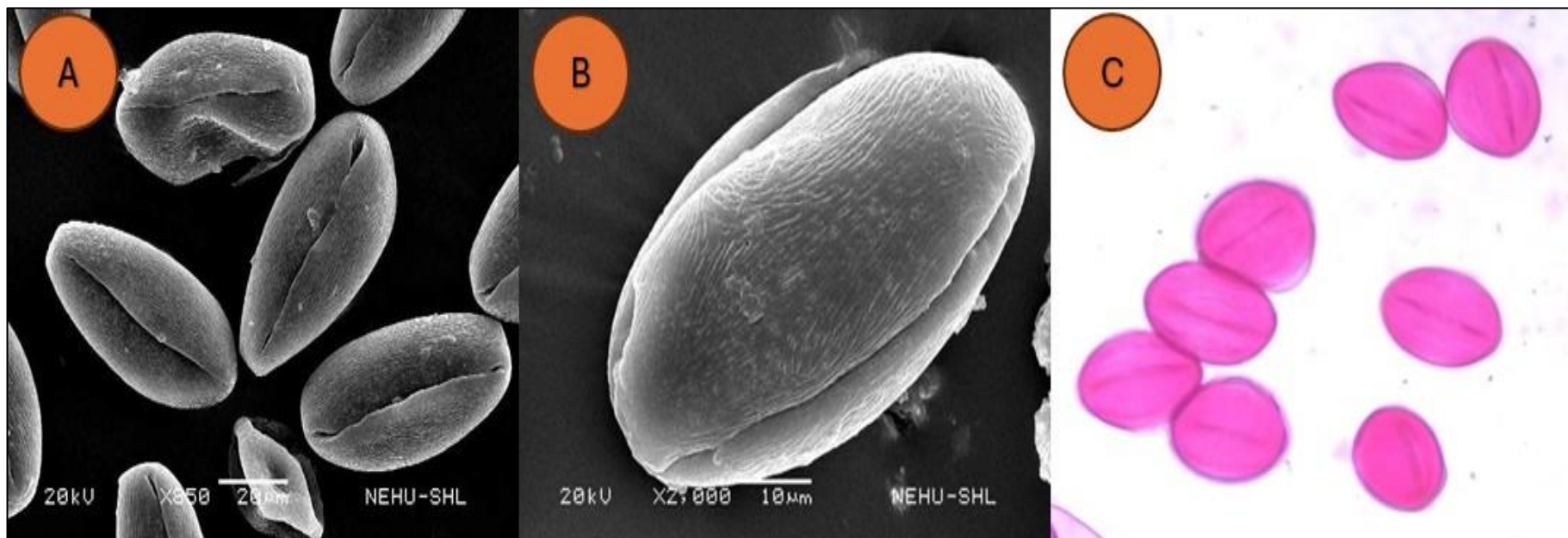


Figure 4. 5 (A-B) Pollen grain of *P. cerasoides* captured using Scanning Electron Microscopy (SEM)
(C) Pollen grain of *P. cerasoides* captured using Light microscope



Figure 4. 6 Pattern of anther dehiscence in Mizoram

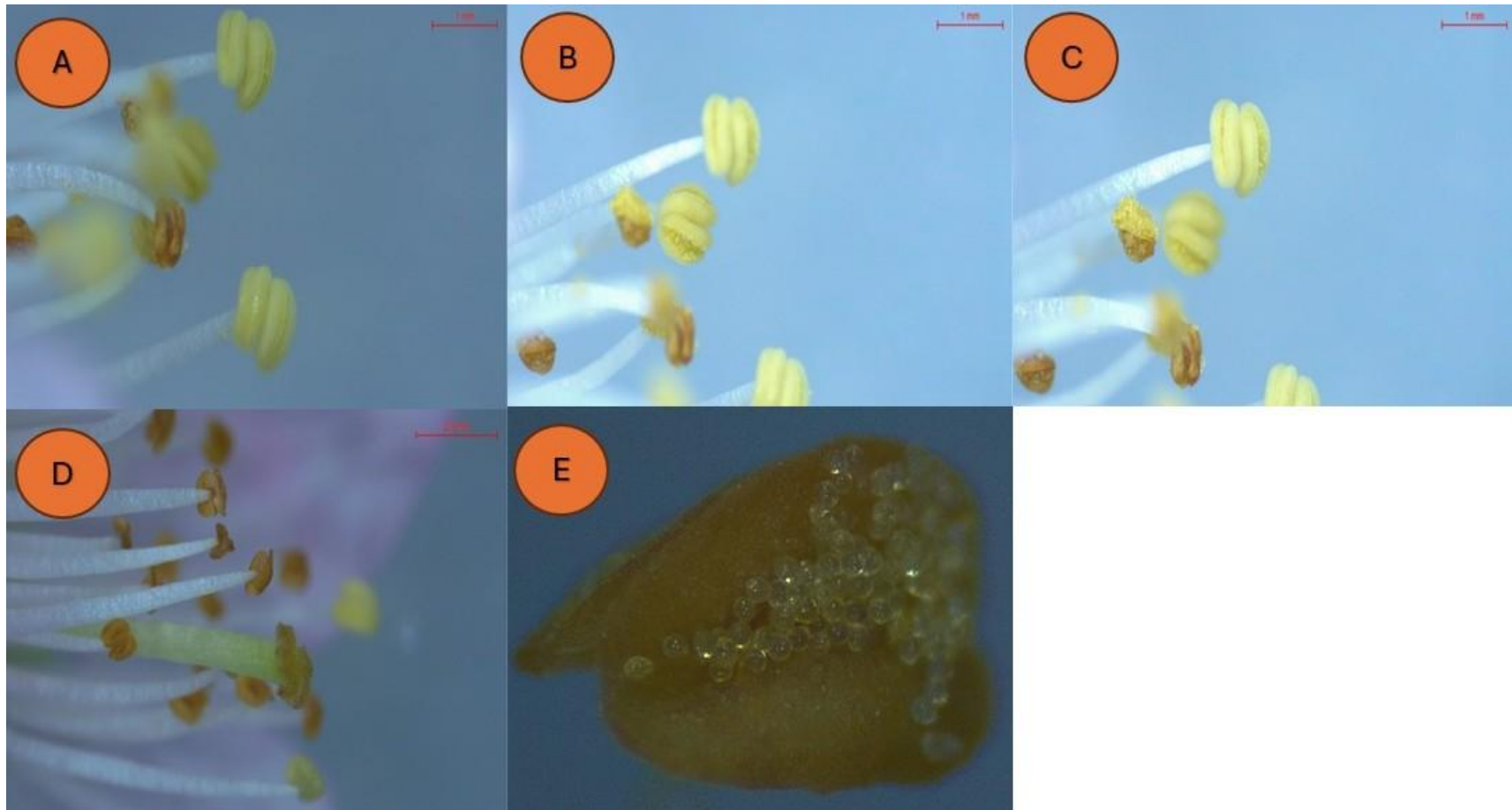


Figure 4. 7 Anther dehiscence in *P. cerasoides* under stereo zoom microscope, showing sequential stages from closed anthers to fully dehiscent anthers



Figure 4. 8 Pattern of stigma receptivity in Mizoram

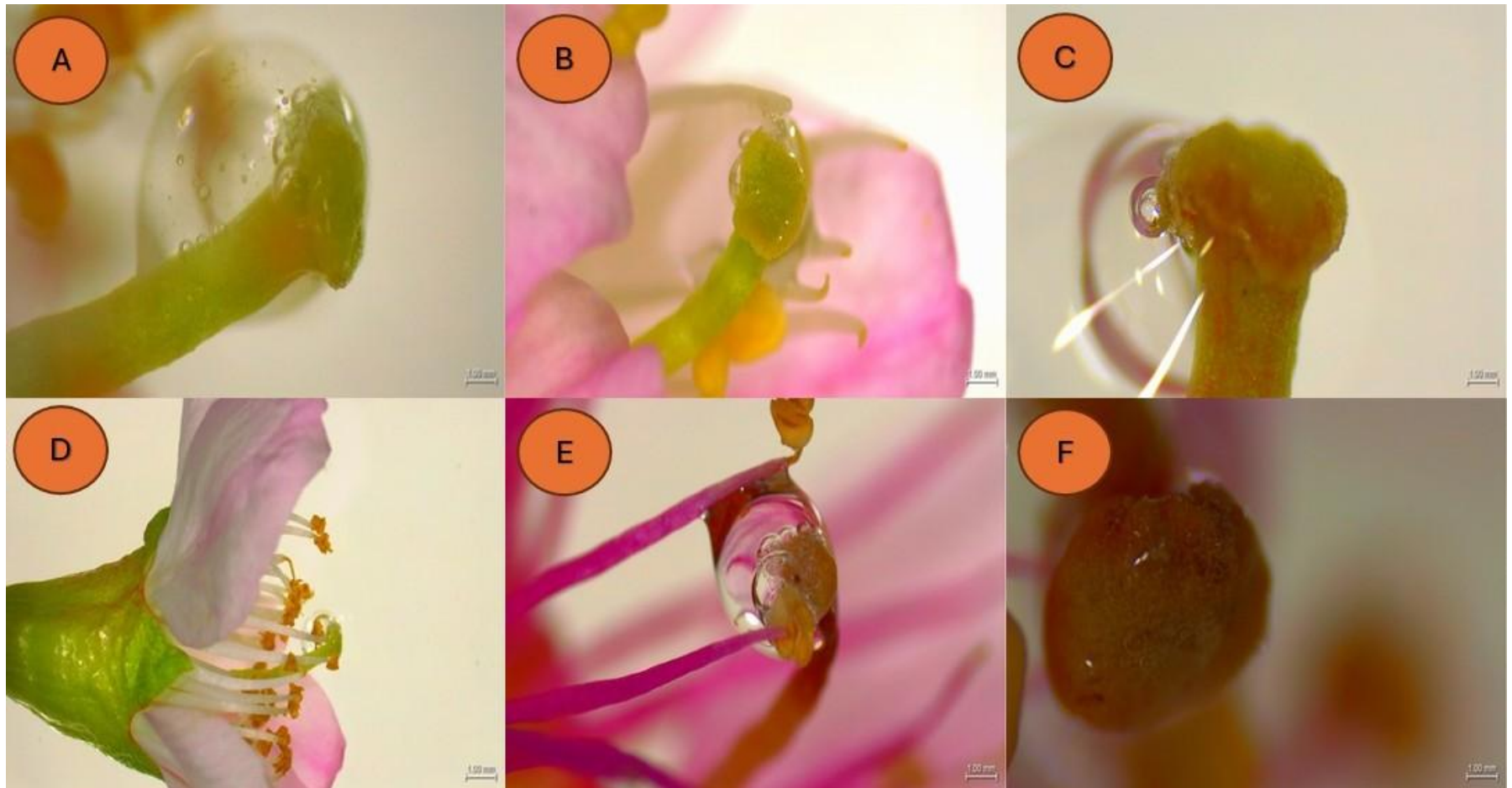


Figure 4. 9 Pattern of stigma receptivity in *P. cerasoides* under stereo zoom microscope

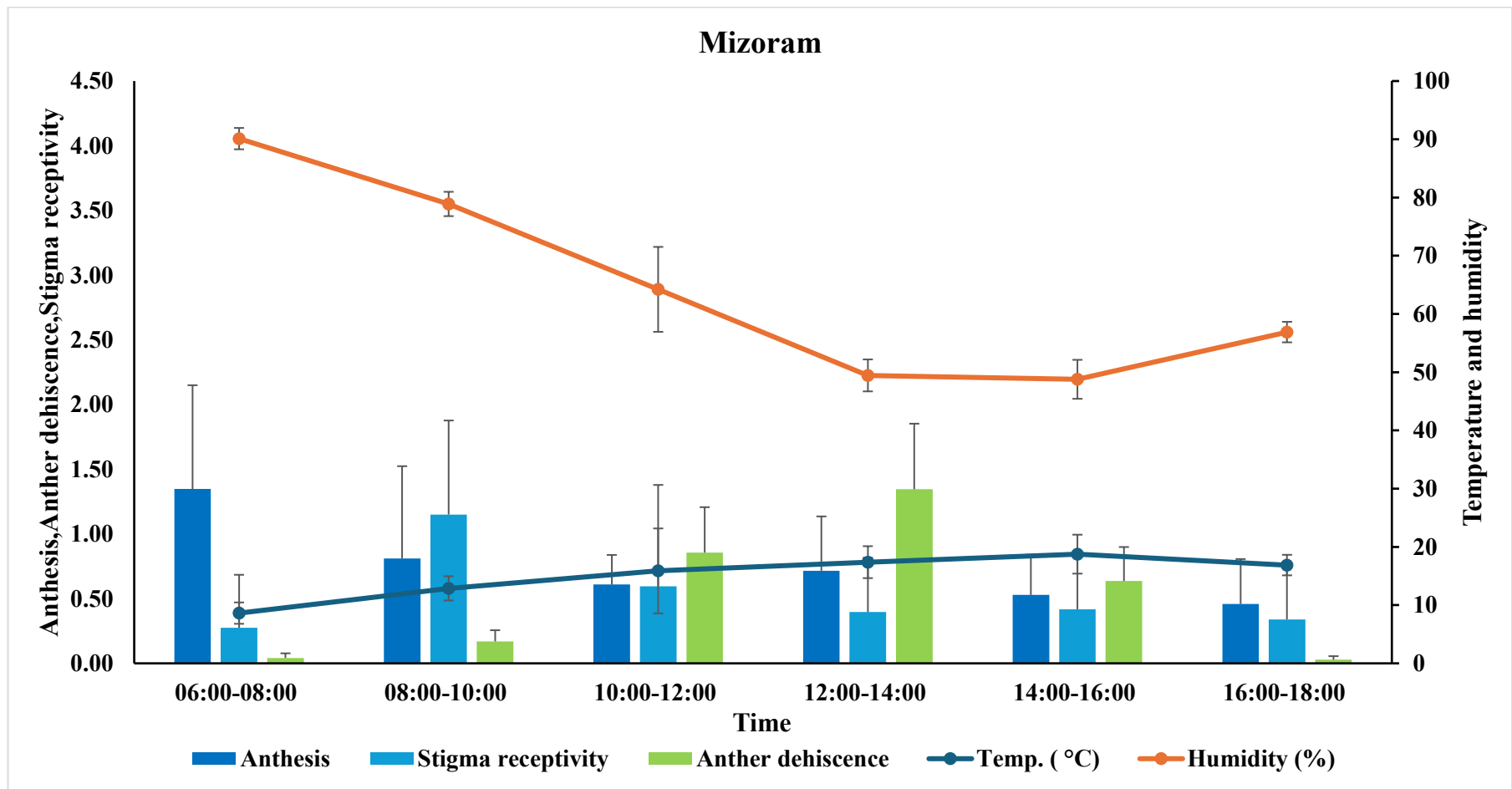


Figure 4. 10 Pattern of anthesis, anther dehiscence and stigma receptivity with respect to temperature and humidity in Mizoram

The period of anthesis has elevated levels throughout the time frame of 06:00 to 08:00, along with a concurrent increase in humidity. Nevertheless, as the day progresses, there is a noticeable decline in humidity levels, which is accompanied by a declining trend in anthesis. Thereafter, there was no anthesis and anther dehiscence taking place at night. Based on SEM observations, the pollen of *P. cerasoides* is characterized by a single-grain (monad) unit. The grains are prolate spheroidal in shape, and they possess three apertures, making them tricolporate. The surface of the pollen is distinctly striate (Figure 4.5).

The trend of anther dehiscence was seen to be most prevalent throughout the time interval of 12:00 to 14:00 hours, while its occurrence was found to be least frequent between 16:00 and 18:00 hours, coinciding with the increasing levels of humidity (Figure 4.6). To understand the anther dehiscence mechanism in detail, a series of stereo zoom images were captured, documenting the process from an unopened state to full dehiscence (Figure 4.7). The anther's development involves a sequential process, transitioning from the pre-dehiscent stage to the full release of its pollen. The figures show the initial longitudinal splitting of the anther lobes, which then allows the pollen to be fully exposed for dispersal. A magnified view of the dehiscent anther, with the pollen grains clearly visible, is also presented. The release of pollen from anthers were found to occur continuously throughout the day, which aligns with an elevated temperature during this period. Furthermore, pollen is released through a longitudinal slit. The study found that stigma receptivity remained consistent during the entire flowering phase. On the other hand, the morning hours of 06:00 and 08:00 showed the least amount of receptivity, while 08:00 and 10:00 showed the greatest, coinciding with the rising temperature (Figure 4.8). There is a noticeable decline in receptiveness to stigma as the day progresses. The figure (4.9) illustrates the pattern of stigma receptivity in stereo zoom, showing its developmental process from the moment of its emergence to its final withered, non-receptive state. Anthesis, stigma receptivity, and anther dehiscence all exhibited diurnal patterns, suggesting that the time of day have an impact on the reproductive processes of *P. cerasoides* (Figure 4.10).

Table 4. 1 Correlation coefficient between climate variables and floral biology in Mizoram

Variables	SR	A	AD	T	H
Stigma Receptivity (SR)	1				
Anthesis (A)	-0.085	1			
Anther Dehiscence (AD)	-0.144	-0.058	1		
Temperature (T)	-0.100	-0.443**	0.463**	1	
Humidity (H)	0.212	0.414**	-0.563**	-0.896**	1

** Correlation is significant at the 0.01 level (2-tailed).

Anthesis exhibits a significant negative correlation with temperature ($r = -0.443$ **, $p < 0.01$) and a significant positive correlation with humidity ($r = 0.414$ **, $p < 0.01$). Anther dehiscence is significantly correlated with multiple factors. A strong positive correlation is observed between anther dehiscence and temperature ($r = 0.463$ **, $p < 0.01$). Conversely, anther dehiscence shows a significant negative correlation with humidity ($r = -0.563$ **, $p < 0.01$). Climatic factors temperature and humidity exhibit a strong negative correlation among them. Temperature and humidity exhibit a strong negative correlation ($r = -0.896$ **, $p < 0.01$) (Table 4.1).

4.2 Floral biology: anthesis, stigma receptivity and anther dehiscence of *P. cerasoides* (Uttarakhand)

The mean height of the tree is 9.962 ± 0.72 m, while the mean girth of the tree is 87.4 ± 7.04 cm. The bloom exhibits a length of 22.00 ± 1.67 mm and a width of 29.70 ± 1.38 mm, and bisexual. The calyx exhibits a green hue and consists of five sepals, measuring 10.74 ± 1.01 mm in length and 4.98 ± 0.61 mm in width. The mean number of stamens was determined to be 35.96 ± 0.96 and 37.12 ± 1.49 for the years 2019 and 2020, respectively. The length of the stamens is measured to be 11.20 ± 0.64 mm, while the anthers have a yellowish coloration. Additionally, the stigma is seen to have a length of 14.86 ± 0.40 mm. In the field of investigation, it was discovered that there was one instance of a stigma, while occurrences of two to four stigmas were rather few

(Figure 4.11). The filament originated as a cluster emerging from the base of the flower adjacent to the calyx wall but gradually diverged towards the distal end of the calyx. *P. cerasoides* possesses a solitary ovule. In the Uttarakhand region, it was discovered that the process of anthesis, the blooming of flowers, typically occurred subsequent to the initiation of floral buds. This initiation process typically spans a duration of approximately 8 to 11 days. During the designated period of observation, it was noted that the process of anthesis took place at various times throughout the day. However, the highest frequency of anthesis was observed between the hours of 08:00 and 10:00, followed by the hours of 06:00 and 08:00. Conversely, the lowest occurrence of anthesis was recorded between the hours of 1600 and 1800 (Figure 4.12). The dehiscence of the anther exhibited a diurnal pattern, similar to that observed during anthesis. The maximum recorded time for anther dehiscence was observed to be between 12:00 and 14:00 hours coinciding with a rise in temperature, while the minimum was observed between 16:00 and 18:00 hours (Figure 4.13). The dispersion of pollen particles into the atmosphere occurred via a longitudinal opening. The absence of both anthesis and dehiscence was noted throughout the nocturnal period. In contrast, stigma receptivity exhibited responsiveness throughout the blossoming period.



Figure 4. 11 Variation in stigma numbers in *P. cerasoides* (Uttarakhand). A. Two numbers of stigmas B. Four numbers of stigmas C. One stigma



Figure 4. 12 Pattern of anthesis in Uttarakhand

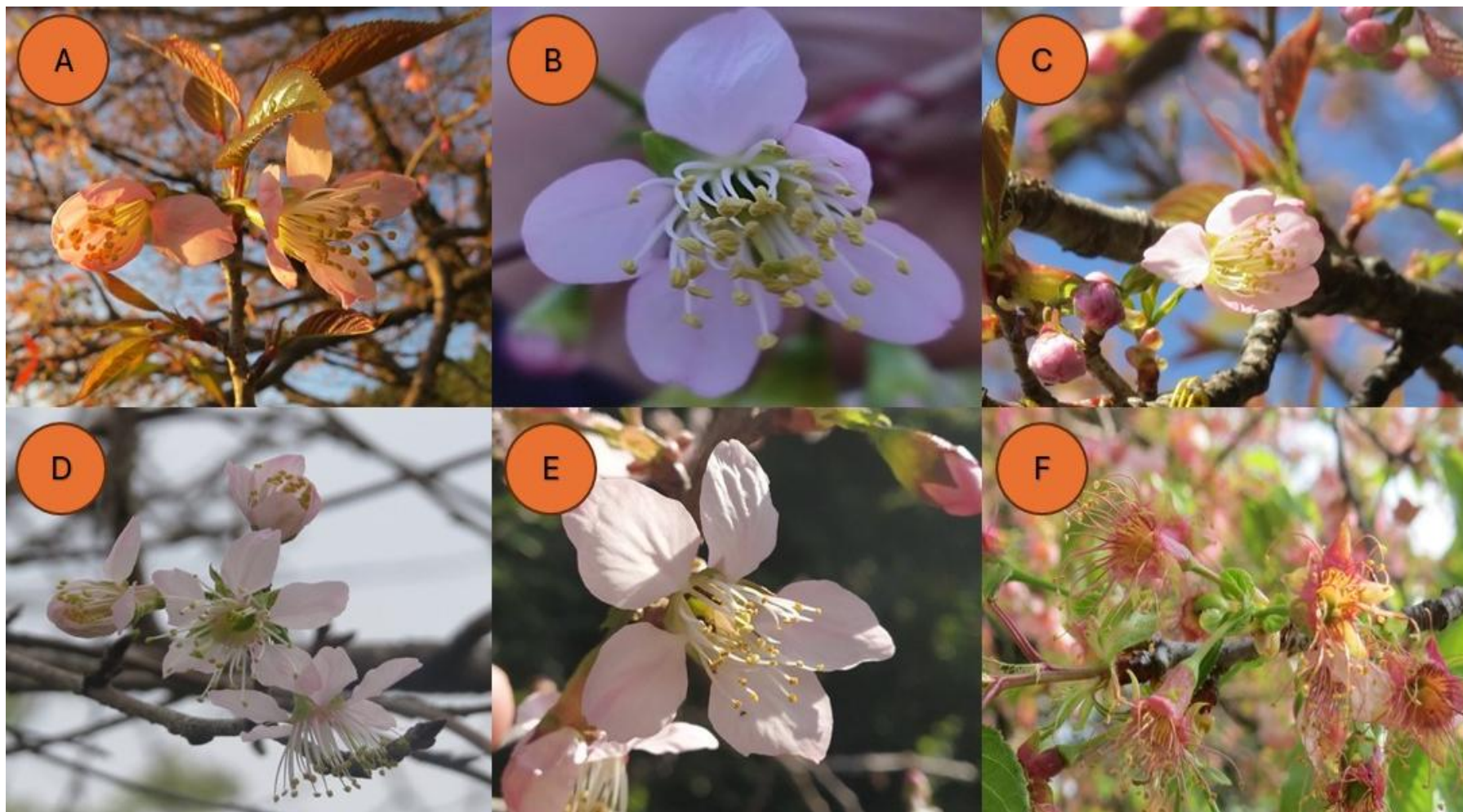


Figure 4. 13 Pattern of anther dehiscence in Uttarakhand



Figure 4. 14 Pattern of stigma receptivity Uttarakhand

The stigma remained responsive despite the shedding of the petals. The results show that stigma receptivity peaked between the hours of 10:00 and 12:00, which is consistent with a concomitant drop in humidity. While the lowest levels were observed between 06:00 and 08:00 (Figure 4.14). With the rise in temperature, anthesis, or a flower opening, seems to be following a trend, peaking between 8:00 and 10:00, coinciding with a rise in temperature. It can be observed that the relationship displayed between humidity and anthesis lacks a discernible pattern. Notably, anthesis also exhibits an increase during this time, and the highest humidity is noted between 6:00 and 8:00. Throughout the day, variations in anthesis, stigma receptivity, and anther dehiscence have been observed. The peak values for these parameters show diurnal patterns in the flower reproductive processes, occurring at different time intervals (Figure 4.15).

A correlation analysis revealed significant associations between floral phenological traits and climatic variables. Temperature showed a significant negative correlation with anthesis ($r = -0.360^{**}$, $p < 0.01$). In contrast, temperature was positively correlated with anther dehiscence ($r = 0.413^{**}$, $p < 0.01$). Although stigma receptivity was positively correlated with temperature ($r = 0.238$), this relationship was not statistically significant.

Humidity exhibited stronger and more consistent negative effects across floral traits. A significant negative correlation was observed between humidity and stigma receptivity ($r = -0.469^{**}$, $p < 0.01$). Similarly, humidity was negatively correlated with anther dehiscence ($r = -0.439^{**}$, $p < 0.01$), while showing a significant positive correlation with anthesis ($r = 0.307^{*}$, $p < 0.05$). Additionally, temperature and humidity were negatively correlated ($r = -0.548^{**}$, $p < 0.01$)(Table 4.2).

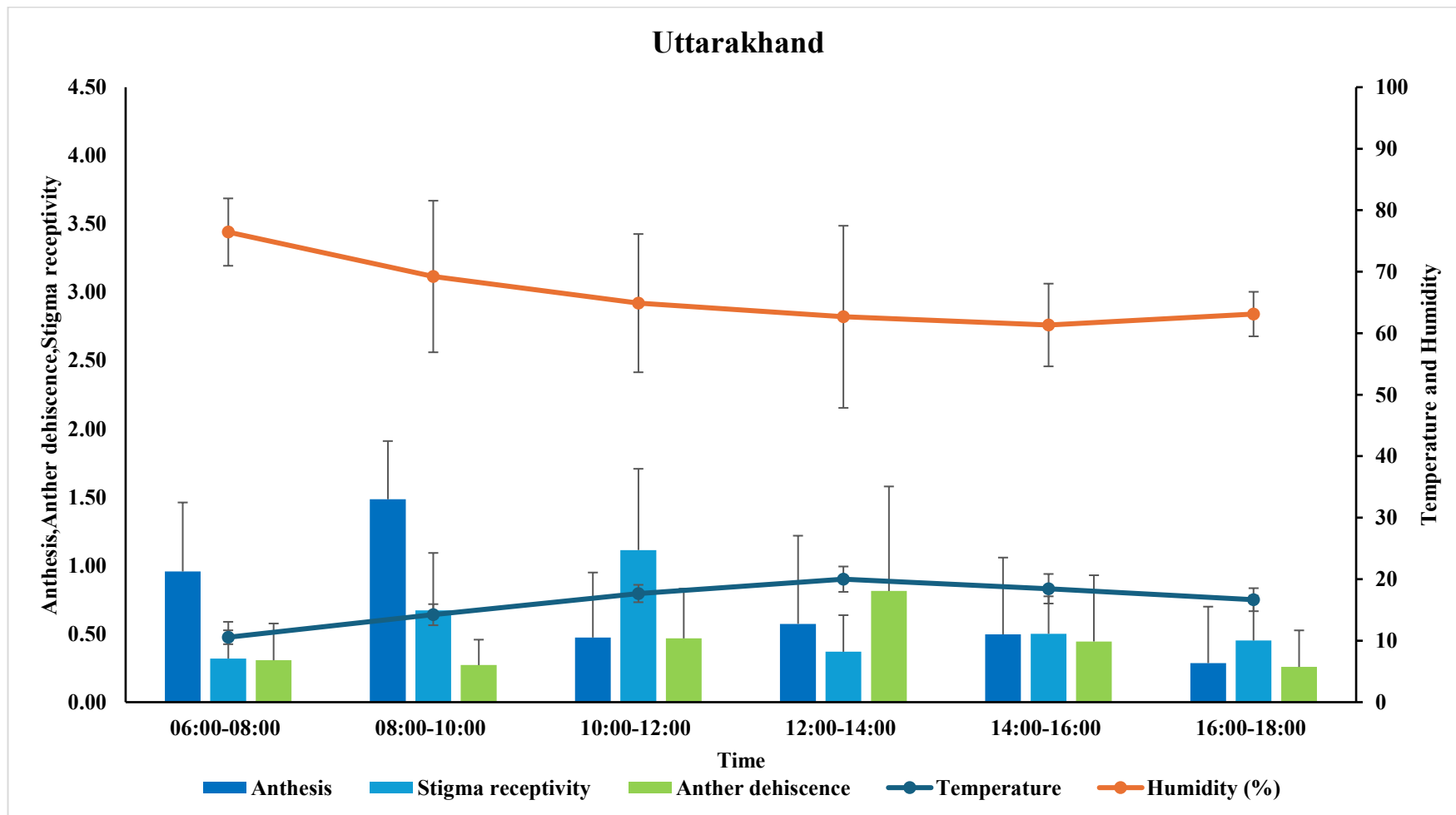


Figure 4. 15 Pattern of anthesis, anther dehiscence and stigma receptivity with respect to temperature and humidity in Uttarakhand

Table 4. 2 Correlation coefficient between climate variables and floral biology in Uttarakhand

Variables	SR	A	AD	T	H
Stigma Receptivity (SR)	1				
Anthesis (A)	-0.174	1			
Anther Dehiscence (AD)	.410**	0.027	1		
Temperature (T)	0.238	-.360**	.413**	1	
Humidity (H)	-.469**	.307*	-.439**	-.548**	1

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

4.3 Assessment of mating system and reproductive compatibility in *P. cerasoides* (Mizoram)

In Mizoram, *P. cerasoides* show partial self-compatibility, according to an evaluation of the mating system conducted in 2019 and 2021. In 2019, *P. cerasoides* exhibited the highest percentage of fruit set under natural pollination conditions, with a mean of 60.05 ± 2.41 . This was followed by open cross-pollination 50.06 ± 1.26 and hand cross-pollination 36.83 ± 0.57 percent fruit set respectively. Hand self-pollination yielded 30.95 ± 0.80 , whereas autogamous self-pollination recorded a much lower fruit set of 29.64 ± 0.47 percent fruit set respectively. Notably, the apomixis treatment resulted in zero percent fruit set, indicating the complete absence of apomictic reproduction during this year (Table 4.3). In 2021, a similar pattern was observed. Natural pollination again produced the highest fruit set (68.99 ± 1.18), followed by open cross-pollination (60.91 ± 1.02) and hand cross-pollination (49.97 ± 0.85) respectively. The mean percent fruit set under hand self-pollination was 46.23 ± 0.66 , while autogamous self-pollination remained low at 39.32 ± 0.54 . The apomixis treatment showed no fruit set, further supporting the absence of apomixis in this species (Table 4.4). Based on the ratio of fruit set in self-pollinated flowers to fruit set in cross-pollinated flowers, the index of self-incompatibility (ISI) (Zapata and Arroyo 1978) was computed.

The findings demonstrated that *P. cerasoides* exhibited index values of 0.84 and 0.92 in the years 2019 and 2021, respectively (Table 4.5). These values lie within the range of >0.2 but 1, indicating partial self-compatibility according to the classification by Zapata and Arroyo (1978). Furthermore, the determination of the outcrossing index involved the assessment of various factors, including the flower's width, the temporal gap between anther dehiscence and stigma receptivity, and the spatial arrangement of stigmas and anthers. The recorded values of *P. cerasoides* were found to be 4, a range that aligns with the classification of >4 as partially self-compatible (Table 4.6). This observation suggests that *P. cerasoides* can be considered partially self-compatible, in accordance with the findings of Cruden, 1977.

Table 4. 3 Mating system Mizoram 2019, ($\pm$) SD

Treatment	Fruit Set Percentage (%) $\pm$ SD
Natural Pollination	60.05 $\pm$ 2.41
Open Cross Pollination	50.06 $\pm$ 1.26
Hand Cross Pollination	36.83 $\pm$ 0.57
Hand Self Pollination	30.95 $\pm$ 0.80
Autogamous Self Pollination	29.64 $\pm$ 0.47
Apomixis	0.00 $\pm$ 0.00

Table 4. 4 Mating system Mizoram 2021, ($\pm$) SD

Treatment	Fruit Set Percentage (%) $\pm$ SD
Natural Pollination	68.99 $\pm$ 1.18
Open Cross Pollination	60.91 $\pm$ 1.02
Hand Cross Pollination	49.97 $\pm$ 0.85
Hand Self Pollination	46.23 $\pm$ 0.66
Autogamous Self Pollination	39.32 $\pm$ 0.54
Apomixis	0.00 $\pm$ 0.00

Table 4. 5 Index of self-incompatibility (ISI) (Zapata and Arroyo 1978)

<i>P. cerasoides</i>	ISI	Type of Mating System as per ISI
Mizoram 2019	0.84	Partially self-compatible
Mizoram 2021	0.92	Partially self-compatible
ISI according to (Zapata and Arroyo 1978)	1 or >1	fully self-compatible
	>0.2 but <1	Partially self-compatible
	<0.2 or 0	self-incompatible

ISI = fruit set in self-pollinated flower/fruit set in cross-pollinated flowers

Table 4. 6 Out crossing Index (Cruden, 1977)

Variables	Points	<i>P. cerasoides</i>
Diameter of the flower	Up to 1mm=0	3
	1-2 mm=1	
	2-6mm=2	
	>6mm =3	
Temporal separation of anther dehiscence & stigma receptivity	Homogamy,	0
	Protogyny=0	
	Protandry=1	
Spatial positioning of stigma & anthers	Same=0	1
	Spatially separated=1	
Outcrossing demand for pollinators	Partially self-compatible	4

0=Cleistogamy, 1=Obligate autogamy, 2=Facultative autogamy, 3=self-compatible, >4=partially self-compatible

4. 4 Assessment of mating system and reproductive compatibility in *P. cerasoides* (Uttarakhand)

The mating system was assessed over a span of two years, specifically in 2019 and 2021, within the region of Uttarakhand. The findings indicate that *P. cerasoides* exhibits partial self-compatibility. In Uttarakhand during 2019, the fruit set percentage varied across different pollination treatments. Natural pollination recorded the highest fruit set at 70.45 ± 1.80 , followed by open cross pollination at 61.69 ± 8.05 . Hand cross pollination and hand self-pollination showed fruit set percentages of 40.25 ± 8.36 and 38.15 ± 10.78 , respectively. Autogamous self-pollination resulted in a fruit set of 34.21 ± 10.10 , while the fruit set observed under Apomixis, was zero. (Table 4.7). In 2021, fruit set percentage in Uttarakhand was highest under Natural Pollination (73.01 ± 2.20), followed by open cross pollination (69.72 ± 1.51). Hand cross pollination recorded 59.19 ± 4.27 , while Hand self-pollination showed 56.24 ± 9.36 . Autogamous self-pollination resulted in 47.80 ± 11.47 , and no fruit set was observed under Apomixis (Table 4.8). According to the Index of Self-Incompatibility (ISI), the ratio of fruit set in self-pollinated flowers to fruit set in cross-pollinated flowers was computed in order to determine the type of mating system. This helped determine the kind of mating system. Based on the results of the computed variables, it was determined that *P. cerasoides* fall within the range of less than 0.2 or zero, which signifies that this species is partially self-compatible, as stated by Zapata and Arroyo in 1978 (Table 4.9). At both of the research sites, the outcrossing index were calculated to be similar (Table 4.10).

Table 4. 7 Mating system Uttarakhand 2019, ($\pm$) SD

Treatment	Fruit Set Percentage (%) $\pm$ SD
Natural Pollination	70.45 $\pm$ 1.80
Open Cross Pollination	61.69 $\pm$ 8.05
Hand Cross Pollination	40.25 $\pm$ 8.36
Hand Self Pollination	38.15 $\pm$ 10.78
Autogamous Self Pollination	34.21 $\pm$ 10.10
Apomixis	0.00 $\pm$ 0.00

Table 4. 8 Mating system Uttarakhand 2021, ($\pm$) SD

Treatment	Fruit Set Percentage (%) $\pm$ SD
Natural Pollination	73.01 $\pm$ 2.20
Open Cross Pollination	69.72 $\pm$ 1.51
Hand Cross Pollination	59.19 $\pm$ 4.27
Hand Self Pollination	56.24 $\pm$ 9.36
Autogamous Self Pollination	47.80 $\pm$ 11.47
Apomixis	0.00 $\pm$ 0.00

Table 4. 9 Index of self-incompatibility (ISI) (Zapata and Arroyo 1978)

<i>P. cerasoides</i>	ISI	Type of Mating System as per ISI
Uttarakhand 2019	0.94	Partially self-compatible
Uttarakhand 2021	0.95	Partially self-compatible
ISI according to (Zapata and Arroyo 1978)	1 or >1	fully self-compatible
	>0.2 but <1	Partially self-compatible
	<0.2 or 0	self-incompatible

ISI = fruit set in self-pollinated flower/fruit set in cross-pollinated flowers

Table 4. 10 Out crossing Index (Cruden, 1977)

Variables	Points	<i>P. cerasoides</i>
Diameter of the flower	Up to 1mm=0	3
	1-2 mm=1	
	2-6mm=2	
	>6mm =3	
Temporal separation of anther dehiscence & stigma receptivity	Homogamy, Protogyny=0 Protandry=1	0
Spatial positioning of stigma & anthers	Same=0	1
	Spatially separated=1	
Outcrossing demand for pollinators	Partially self-compatible	4

0=Cleistogamy, 1=Obligate autogamy, 2=Facultative autogamy, 3=self-compatible, >4=partially self-compatible

4. 5 Assessment of pollen production, pollen/ovule ratio in *P. cerasoides* from Mizoram and Uttarakhand

The average height and girth of *P. cerasoides* exhibited variation across two distinct geographical locations. Between the two distinct geographic areas, there were differences in pollen production. The annual bloom yield per tree exhibited variability throughout multiple years in two distinct geographical areas. A positive trend was identified in floral abundance between the years 2019 and 2021, with a little rise in the average number of flowers per sub-branch recorded in Mizoram (1070.33 ± 151.07 , 1139.94 ± 173.69) and Uttarakhand (1366.19 ± 189.19 , 1367.70 ± 187.59), respectively. A discrepancy in the production of pollen grains per plant was noted between the two study sites. The year 2019 witnessed a higher production of pollen grains per plant in Uttarakhand, while Mizoram experienced the lowest production of pollen grains per plant during the same year. The *P. cerasoides* species in Mizoram exhibited an estimated average pollen production per tree of 1.2×10^9 in 2019 and 1.8×10^9 in 2021. In the years 2019 and 2021, the total pollen output in Uttarakhand was recorded as 2.6×10^9 and 2.4×10^9 , respectively. The quantity of stamens per flower exhibited

variability between different years and even between the two designated study sites. The stamen measurements recorded in Mizoram were 35.96 ± 0.96 and 37.12 ± 1.49 . The mean values for Uttarakhand are 34.56 ± 1.78 and 33.42 ± 1.52 , respectively. In the year 2019, Uttarakhand exhibited notable pollen production, whereas Mizoram achieved the highest level of pollen production in the year 2021. The fruit setting per tree in Uttarakhand reached its highest recorded value in the year 2021, with an average of 9978.83 ± 1598.98 . Although there was a notable increase in pollen production in Mizoram in the year 2021, the percentage of successful fruit setting (955.37 ± 286.56) appears to be lower compared to the previous year, 2019, when the fruiting set yielded favorable outcomes (Table 4.11). The pollen-ovule ratio for the species was determined to be $43,092.85 \pm 5467.78$. According to Cruden's (1977) classification, this value falls into the xenogamy category, which is defined by a pollen-ovule ratio greater than 11,400

Table 4. 11 Annual production of flower, pollen and fruit per tree (N=10 trees)

Observed variables	Mizoram		Uttarakhand	
	2019	2021	2019	2021
Average Girth (cm)	77.8 ±0.67	77.8±0.67	87.4±7.04	87.4±7.04
Average height (m)	8.815±5.05	8.815±0.67	9.962±0.72	9.962±0.72
Flowers /subbranch	1070.33±151.07	1139.94±173.69	1366.19±189.19	1367.70±187.59
No. of subbranch/ main branches	7.54±1.10	7.54±1.09	6.46±0.81	6.46±0.80
No. of main branches / tree	5.70±1.57	5.70±1.56	6.40±1.17	6.40±1.17
Flower per tree	34481.61± 5143.03	41819.55 ±5537.97	55154.40±7033.18	55013.87±4807.22
Stamens/flower	35.96±0.96	37.12±1.49	34.56±1.78	33.42±1.52
Pollen grain/anther	975.10±49.27	1204.02 ±63.17	1363.86±117.58	1358.57±90.53
Pollen grain/flower	35057.84 ±1883.37	44681.06 ±2697.22	47271.68±6113.62	45360.82±3041.10
Total pollen grain/tree (x10 ⁹)	1.2±0.1	1.8±0.2	2.6±0.4	2.4±0.2
Pollen ovule ratios	35057.84 ±1883.37	44681.06 ±2697.22	47271.68±6113.62	45360.82±3041.10
Fruit setting per tree	1066.23±224.98	955.37±286.56	7234.50±1156.92	9978.83±1598.98

Table 4. 12 Pollen ovule ratio in *P. cerasoides*

Plant species	Pollen/ovule ratio	Type of Mating system as P/O ratio	Standard range value Cruden, 1977
<i>Prunus cerasoides</i>	43,092.85 $\pm$ 5467.78	Xenogamy	>11,400

Table 4. 13 ANOVA between years, population and population*years

Response variable and source	df	MS	F	P
Anther per flower				
Year	1	0.001	0.000462	0.982963
Population	1	65.025	30.0655	0.00000341
Population * Years	1	13.225	6.114821	0.018262
Pollen per anther				
Year	1	715284.7	23.76921	0.000022
Population	1	134605.7	4.473004	0.041423
Population * Years	1	16684.73	0.55444	0.461342
Total pollen per flower				
Year	1	923941103	23.54	2.3611E-05
Population	1	4772010.18	0.122	0.729
Population * Years	1	94402658.8	2.405	0.13
Total pollen per tree				
Year	1	3.1135E+18	41.862	1.6434E-07
Population	1	5.3423E+18	71.829	4.2423E-10
Population * Years	1	1.4759E+16	0.198	0.659
Fruit set per tree				
Year	1	17337866.3	17.218	0.0002
Population	1	576971902	572.968	1.0569E-23
Population * Years	1	20380417.1	20.239	6.8709E-05

Significant variation in the number of anthers per flower was observed among populations ($F = 30.07$, $p < 0.001$), and a significant interaction between population and year was also detected ($F = 6.11$, $p < 0.05$). No significant difference was found between years ($p = 0.983$). Pollen production per anther differed significantly between years ($F = 23.77$, $p < 0.001$) and among populations ($F = 4.47$, $p < 0.05$). The interaction between population and year was not significant ($p = 0.461$). Total pollen per flower varied significantly between years ($F = 23.54$, $p < 0.001$), while no significant differences were observed among populations ($p = 0.729$) or in the population-by-year interaction ($p = 0.130$). Total pollen per tree showed significant differences between years ($F = 41.86$, $p < 0.001$) and among populations ($F = 71.83$, $p < 0.001$). The interaction between population and year was not significant ($p = 0.659$). Fruit set per tree differed significantly between years ($F = 17.22$, $p < 0.001$), among populations ($F = 572.97$, $p < 0.001$), and also showed a significant interaction between population and year ($F = 20.24$, $p < 0.001$) (Table 4.13).

Linear regression analyses were performed to assess the relationship between floral traits and fruit set in *P. cerasoides* (Figures 4.16 and 4.17). In Mizoram, a positive linear relationship was observed between the total number of flowers per tree and the fruit set percentage per tree ($R^2=0.5145$; Figure 4.16). A similar positive relationship was found between total pollen per tree and fruit set percentage per tree ($R^2=0.4319$; Figure 4.17).

In Uttarakhand, the relationship between the total number of flowers per tree and fruit set percentage per tree was also positive ($R^2=0.6237$; Figure 4.18). The strongest relationship was observed between total pollen per tree and fruit set percentage per tree ($R^2=0.6661$; Figure 4.19).

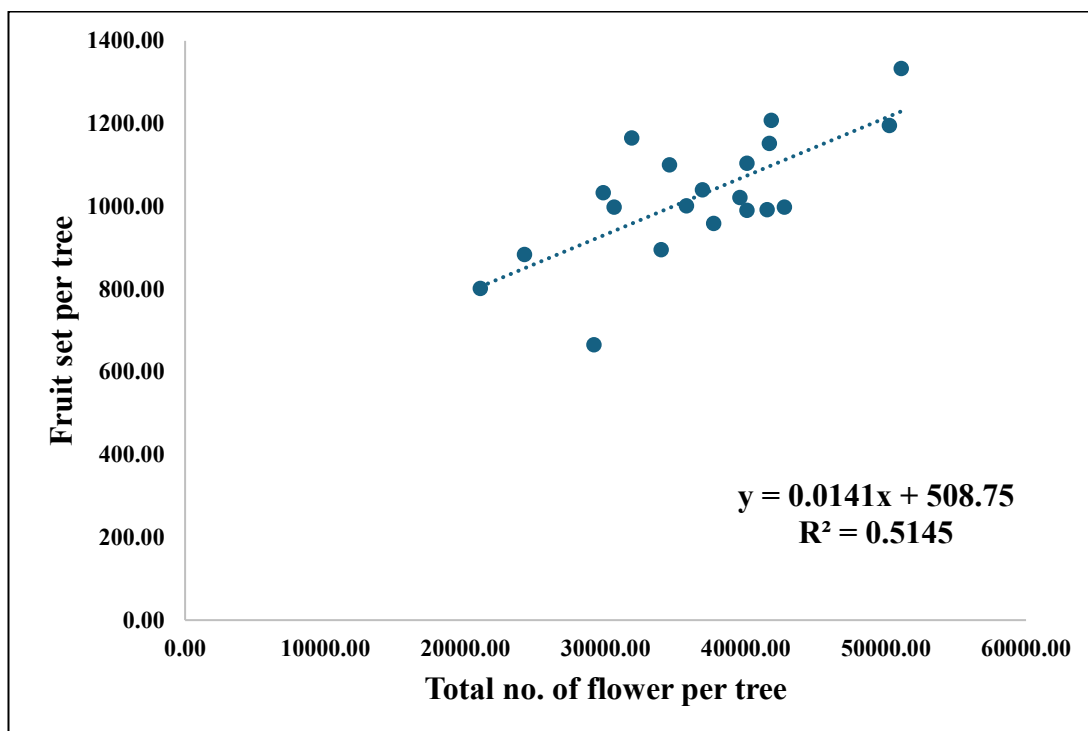


Figure 4. 16 Regression line Total No. of flower/ tree and Fruit set/ tree, Mizoram

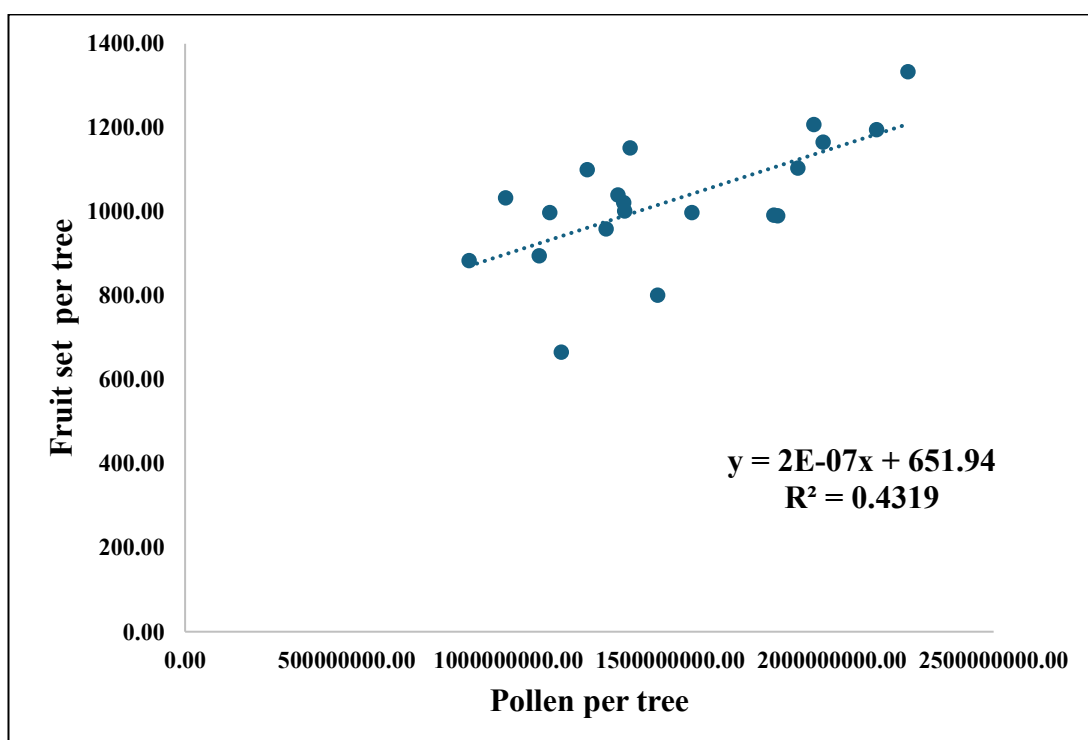


Figure 4. 17 Regression line Total No. of flower/ tree and Fruit set / tree, Uttarakhand

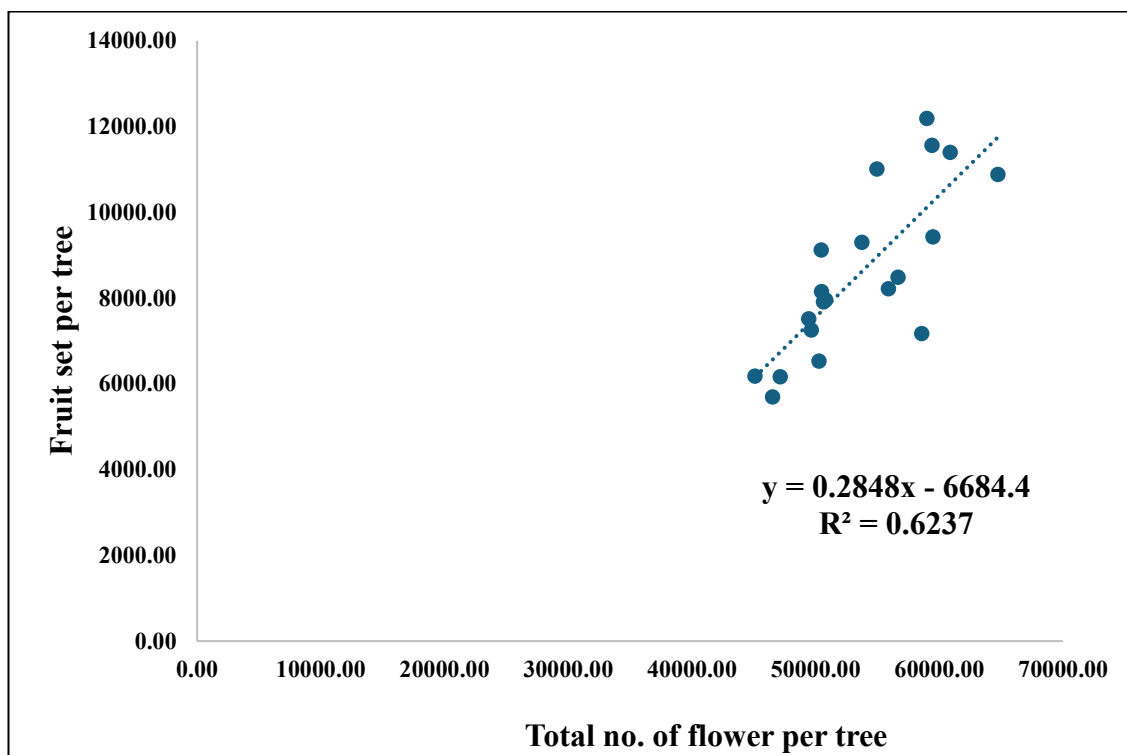


Figure 4. 18 Regression line Pollen grain / tree and Fruit set / tree, Mizoram

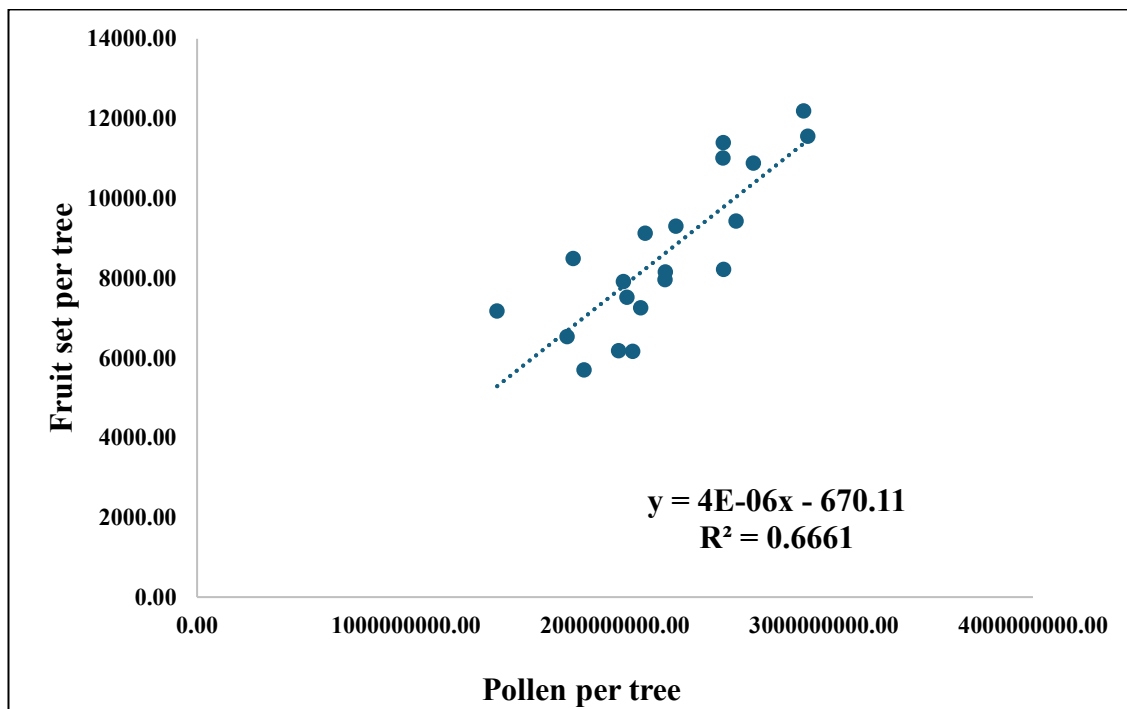


Figure 4. 19 Regression line Pollen grain / tree and Fruit set / tree, Uttarakhand

Table 4. 14 Correlation coefficient between Pollen/ anther, Anther/ Flower, Total pollen / flower, Flowers /sub branch, No. of sub branch/ main branches, No. of main branches / tree, Flower / tree, Pollen /tree, Pollen ovule ratio, Fruit set per tree in *P. cerasoides* (Mizoram, 2019)

Parameters	P/A	A/F	TP/F	F/SB	NSB/M B	NMB /T	F/T	P/T	POR	FS/T
Pollen per anther (P/A)	1									
Anther per Flower (A/F)	-0.161	1								
Total pollen per flower (TP/F)	.863**	0.358	1							
Flowers per sub-branch (F/SB)	-0.343	0.066	-0.294	1						
No. of sub-branch/main br. (NSB/MB)	-0.54	0.354	-0.322	-0.024	1					
No. of main branches/tree (NMB/T)	0.258	-0.291	0.093	-.653*	-0.447	1				
Flower per tree (F/T)	-0.11	-0.317	-0.263	-0.518	0.152	.648*	1			
Pollen per tree (P/T)	0.205	-0.189	0.101	-0.632	0.042	.691*	.932**	1		
Pollen ovule ratio (POR)	.863**	0.358	1.000**	-0.294	-0.322	0.093	-0.263	0.101	1	
Fruit set per tree (FS/T)	-0.363	-0.025	-0.358	-0.121	0.436	0.079	0.358	0.241	-0.358	1

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 4. 15 Correlation coefficient between Pollen/ anther, Anther/ Flower, Total pollen / flower, Flowers /sub branch, No. of sub branch/ main branches, No. of main branches / tree, Flower / tree, Pollen /tree, Pollen ovule ratio, Fruit set per tree in *P. cerasoides* (Mizoram, 2021)

Parameters	P/A	A/F	TP/F	F/SB	NSB/M B	NMB/ T	F/T	P/T	POR	FS/T
Pollen per anther (P/A)	1									
Anther per Flower (A/F)	0.313	1								
Total pollen per flower (TP/F)	.978**	0.499	1							
Flowers per sub-branch (F/SB)	-0.115	0.52	-0.002	1						
No. of sub-branch/main br. (NSB/MB)	-0.394	-0.118	-0.376	-0.257	1					
No. of main branches/tree (NMB/T)	0.195	-0.59	0.046	-0.591	-0.447	1				
Flower per tree (F/T)	-0.569	-.823**	-.685*	-0.439	0.103	0.522	1			
Pollen per tree (P/T)	0.118	-.720*	-0.04	-0.562	-0.257	.804**	.738*	1		
Pollen ovule ratio (POR)	.978**	0.499	1.000**	-0.002	-0.376	0.046	-.685*	-0.04	1	
Fruit set per tree (FS/T)	0.065	0.054	0.072	-0.588	-0.038	0.338	0.014	0.015	0.072	1
** Correlation is significant at the 0.01 level (2-tailed).										
* Correlation is significant at the 0.05 level (2-tailed).										

A correlation analysis among floral and reproductive traits of *P. cerasoides* in Mizoram during 2019 revealed that the pollen per anther showed a very strong positive correlation with pollen ovule ratio ($r=0.863^{**}$), and a strong positive correlation with total pollen per flower ($r=0.863^{**}$). Anther per flower had a strong negative correlation with total pollen per flower ($r=-0.358$). Total pollen per flower exhibited a very strong positive correlation with pollen ovule ratio ($r=1.000^{**}$), and a strong positive correlation with pollen per anther ($r=0.863^{**}$). Flowers per sub branch did not show a strong correlation with any other variable. The number of sub branch per main branches had a weak negative correlation with the number of main branches per tree ($r=-0.447$), and a weak positive correlation with pollen per tree ($r=0.042$). The number of main branches/tree had a weak negative correlation with flowers per sub branch ($r=-0.653$) and the number of sub branch per main branches ($r=-0.447$). Flower per tree showed a very strong positive correlation with pollen per tree ($r=0.932^{**}$). Pollen per tree exhibited a very strong positive correlation with flower per tree ($r=0.932^{**}$). Pollen ovule ratio had a very strong positive correlation with pollen per anther ($r=0.863^{**}$) and total pollen per flower ($r=1.000^{**}$). Fruit set did not show a strong correlation with any other variable (Table 4.14).

In Mizoram, 2021, a correlation analysis showed that the number of pollen grains per anther shows a strong positive correlation with both the total pollen per flower ($r=0.978^{**}$) and the pollen ovule ratio ($r=0.978^{**}$). Conversely, there is a strong negative correlation between the number of anthers per flower and the total number of flowers per tree ($r=-0.823^{**}$). Additionally, a negative correlation was observed between total pollen per flower and flower per tree ($r=-0.685^{*}$). The number of main branches per tree showed a strong positive correlation with total pollen per tree ($r=0.804^{**}$), which in turn had a positive correlation with the number of flowers per tree ($r=0.738^{*}$). The pollen ovule ratio was also found to be negatively correlated with the number of flowers per tree ($r=-0.685^{*}$) (Table 4.15).

The correlation analysis revealed several significant relationships among the reproductive traits of *P. cerasoides* in Uttarakhand 2019. Pollen per anther showed a strong negative correlation with anther per flower ($r = -0.853^{**}$), a very strong positive correlation with total pollen per flower ($r = 0.980^{**}$), a strong positive correlation with pollen per tree ($r = 0.804^{**}$), and a very strong positive correlation with pollen ovule ratio ($r = 0.980^{**}$). Anther per flower had a strong negative correlation with total pollen per flower ($r = -0.712^{**}$) and a strong negative correlation with pollen ovule ratio ($r = -0.712^{**}$). Total pollen per flower exhibited a very strong positive correlation with pollen ovule ratio ($r = 1.000^{**}$) and a strong positive correlation with pollen per tree ($r = 0.813^{**}$). Flowers per sub branch did not show a strong significant correlation with other variables, though it had a weak negative correlation with the number of main branches per tree ($r = -0.664^{*}$). The number of sub branch per main branches had a strong negative correlation with flower per tree ($r = -0.867^{**}$). The number of main branches per tree showed a weak negative correlation with flower per tree ($r = -0.31$). Flower per tree demonstrated a weak negative correlation with pollen per tree ($r = -0.02$). Pollen per tree exhibited a strong negative correlation with anther per flower ($r = -0.596$) and a strong positive correlation with total pollen per flower ($r = 0.813^{**}$). Pollen ovule ratio had a very strong positive correlation with total pollen per flower ($r = 1.000^{**}$) and a strong positive correlation with pollen per anther ($r = 0.980^{**}$). Fruit set per tree had a strong positive correlation with flower per tree ($r = 0.714^{*}$) and a weak negative correlation with the number of sub branch per main branches ($r = -0.188^{**}$) (Table 4.16).

Table 4. 16 Correlation coefficient between Pollen/ anther, Anther/ Flower, Total pollen / flower, Flowers /sub branch, No. of sub branch/ main branches, No. of main branches / tree, Flower / tree, Pollen /tree, Pollen ovule ratio, Fruit set per tree in *P. cerasoides* (Uttarakhand, 2019)

Parameters	P/A	A/F	TP/F	F/SB	NSB/ MB	NMB/T	F/T	P/T	POR	FS/T
Pollen per anther (P/A)	1									
Anther per Flower (A/F)	-.835**	1								
Total pollen per flower (TP/F)	.980**	-.712*	1							
Flowers per sub-branch (F/SB)	0.228	-0.023	0.278	1						
No. of sub-branch/main br. (NSB/MB)	0.394	-0.275	0.407	-0.129	1					
No. of main branches/tree (NMB/T)	-0.388	0.264	-0.4	-.664*	-0.31	1				
Flower per tree (F/T)	-0.577	0.416	-0.595	-0.444	-0.526	.867**	1			
Pollen per tree (P/T)	.804**	-0.596	.813**	0.03	0.094	0.138	-0.02	1		
Pollen ovule ratio (POR)	.980**	-.712*	1.000**	0.278	0.407	-0.4	-0.595	.813**	1	
Fruit set per tree (FS/T)	0.014	-0.134	-0.038	-0.241	-0.188	.732*	.714*	0.458	-0.038	1

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 4. 17 Correlation coefficient between Pollen/ anther, Anther/ Flower, Total pollen / flower, Flowers /sub branch, No. of sub branch/ main branches, No. of main branches / tree, Flower / tree, Pollen /tree, Pollen ovule ratio, Fruit set per tree in *P. cerasoides* (Uttarakhand, 2021)

Parameters	P/A	A/F	TP/F	F/SB	NSB/ MB	NMB/T	F/T	P/T	POR	FS/T
Pollen per anther (P/A)	1									
Anther per Flower (A/F)	-0.342	1								
Total pollen per flower (TP/F)	.774**	0.329	1							
Flowers per sub-branch (F/SB)	-0.166	-0.304	-0.387	1						
No. of sub-branch/main br. (NSB/MB)	-0.505	0.177	-0.383	-0.335	1					
No. of main branches/tree (NMB/T)	0.544	0.02	0.572	-.694*	-0.31	1				
Flower per tree (F/T)	0.117	-0.191	-0.001	-0.446	0.307	0.589	1			
Pollen per tree (P/T)	0.595	0.042	0.634*	-0.568	-0.027	0.818**	.771**	1		
Pollen ovule ratio (POR)	.725*	-0.132	0.627	-0.011	-0.385	0.439	0.268	.641*	1	
Fruit set per tree (FS/T)	0.084	-0.017	0.092	0.297	-0.384	-0.026	-0.231	-0.11	0.051	

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

The correlation analysis of *P. cerasoides* in Uttarakhand 2021 revealed several significant relationships among reproductive traits. Pollen per anther showed a strong positive correlation with total pollen per flower ($r = 0.774^{**}$) and a strong positive correlation with pollen ovule ratio ($r = 0.725^{*}$). Anthe per flower had a strong positive correlation with pollen per tree ($r = 0.654^{*}$). Total pollen per flower exhibited a strong negative correlation with the number of main branches per tree ($r = -0.694^{*}$). Flowers per sub branch did not show a strong significant correlation with any other variable. The number of sub branch per main branches had a strong positive correlation with pollen per tree ($r = 0.818^{**}$). The number of main branches per tree showed a weak negative correlation with the number of sub branch per main branches ($r = -0.31$). Flower per tree demonstrated a strong positive correlation with pollen per tree ($r = 0.771^{**}$). Pollen per tree exhibited a strong positive correlation with anther per flower ($r = 0.654^{*}$), a strong positive correlation with the number of sub branch per main branches ($r = 0.818^{**}$), and a strong positive correlation with flower per tree (0.771^{**}). Pollen ovule ratio had a strong positive correlation with pollen per anther ($r = 0.725^{*}$) and a strong positive correlation with pollen/tree ($r = 0.654^{*}$). Fruit set per tree did not show a strong significant correlation with any other variable (Table 4.17).

4.6 Phenological patterns of flowering and fruiting in *P. cerasoides* across Mizoram and Uttarakhand (2019–2023)

The data from Mizoram indicate that *P. cerasoides* exhibited varying flowering start dates over the four years: November 25th in 2021, December 3rd in 2020, December 2nd in 2019, and November 8th in 2022. These dates indicate variations in the beginning of flowering from year to year. On the hand when considering the perspective of the population as a whole we also observed differences in flowering start dates over the years; December 18th in 2021 December 4th in 2020 December 5th in 2019 and November 16th, in 2022.

Table 4. 18 Variation in reproductive phenology of *P. cerasoides* during four successive years at Mizoram

Observed Variables	2019-20	2020-21	2021-22	2022-23
Onset (mean plant values)	2 nd December	3 rd December	25 th November	8 th November
Onset (population)	5 th December	4 th December	18 th December	16 th November
Peak flowering (Plant)	16 th December	17 th December	9 th December	21 st November
Peak flowering (Population)	17 th December	16 th December	1 st December	29 th November
Flowering duration (Plant)	27.7±0.95 days	25.2±0.42 days	26.6±0.84 days	24.2±0.63 days
Flowering duration (Population)	35 days	33 days	34 days	32 days
Last flowering	30 th December	28 th December	22 nd December	3 rd December
Mean flowering amplitude (per branch per 2 hour)	2.96 ± 0.17	2.61 ± 0.49	2.65±0.55	2.91 ± 0.18
Flowering synchrony	0.81	0.76	0.78	0.75
Fruit set (%)	60.05± 2.41	60.87± 0.87	68.99± 1.18	62.27± 0.88
Fruit drop	15 th March, 2020	25 th March, 2021	12 th March, 2022	9 th March, 2023

These dates provide insights into the annual variation in the timing of flowering onset in Mizoram, suggesting that the onset can vary significantly from year to year, the peak flowering of individual plants in Mizoram happened at different times each year: Those are on December 9th, 2021; December 17th, 2020; December 16th, 2019, and lastly, November 21st, 2022. The timing of peak flowering shows some variability with dates observed for the population over the years; December 1st in 2021 December 16th in 2020 December 17th in 2019 and November 29th in 2022. This similarity to plant data indicates that there is indeed variation in when peak flowering occurs.

The data suggests that individual plants consistently have a duration of flowering each year ranging from around 24.2 to 27.7 days over the four-year period. On the hand the population as a whole has a flowering duration ranging from 32 to 35 days across different years. The final flowering event also happened on dates each year; December 22nd in 2021 December 28th in 2020 December 30th in 2019. December 3rd in 2022. The average flowering amplitude (per branch per 2 hour) slightly varies from year to year. Generally, it remains consistent at around 2.6 to 2.9. Throughout the years the level of synchronization, among flowering events (flowering synchrony) ranged between 0.75 and 0.81.

These results indicate that the population consistently exhibits a level of synchronization in its timing of flower blooming. Over the flowering seasons, the percentage of fruit set varied annually, with recorded values of 60.05 ± 2.41 , 60.87 ± 0.87 , 68.99 ± 1.18 , and 62.27 ± 0.88 . These fluctuations in fruit set were consistent with the observed variability in overall fruit production. The dates on which the fruits fell varied from year to year, with March 9th in 2023, March 12th in 2022, March 25th in 2021, and March 15th in 2020 being the most recent.

The data from Mizoram reveal changes in the timing of flowering events (when they began and peaked), how long they lasted, and other fruit production characteristics

Year	Reproductive Phenophase	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
2019-2020	Flowering& Fruiting (UK)									
	Flowering &Fruiting(MZ)									
2020-2021	Flowering& Fruiting (UK)									
	Flowering &Fruiting(MZ)									
2021-2022	Flowering& Fruiting (UK)									
	Flowering &Fruiting(MZ)									
2022-2023	Flowering& Fruiting (UK)									
	Flowering &Fruiting(MZ)									

Flowering (UK) Fruiting (UK) Flowering (MZ) Fruiting (MZ)

Figure 4. 20 Phenogram of flowering and fruiting phase of *P. cerasoides* at two distinct eco-regions, Uttarakhand (UK) and Mizoram (MZ), India

Table 4. 19 Variation in reproductive phenology of *P. cerasoides* during four successive years at Uttarakhand

Observed Variables	2019-20	2020-21	2021-22	2022-23
Onset (mean plant values)	20 th October	14 th November	26 th October	9 th October
Onset (population)	17 th October	9 th November	19 th October	2 nd October
Peak flowering (Plant)	28 th October	24 th November	5 th November	19 th October
Peak flowering (Population)	24 th October	17 th November	29 th October	12 th October
Flowering duration (Plant)	22.2 ± 1.23 days	23.1 ± 0.99 days	24.8 ± 1.32 days	23.4 ± 0.70 days
Flowering duration (Population)	32 days	30 days	33 days	33 days
Last flowering	11 th November	7 th December	17 th November	1 st November
Mean flowering amplitude (per branch per 2 hour)	3.67±0.70	3.17± 0.15	4.04 ± 0.29	3.15 ± 0.37
Flowering synchrony	0.69	0.77	0.75	0.70
Fruit set (%)	70.45±1.80	71.86± 2.10	73.01± 2.20	75.55± 3.76
Fruit drop	17 th January, 2020	9 th February, 2021	1 st February, 2022	29 th January, 2023

during the four years. This result may be demonstrating on how the seasonal influences the phenology pattern of *P. cerasoides* in Mizoram (Table 4.18, Figure 4.20). These findings underscore the impact of seasonal variation on the phenological behavior of *P. cerasoides* in Mizoram. The distinct stages of reproductive development observed in the study sites are illustrated in (Figure 4.21).

In Uttarakhand, the flowering start dates for the average plants ranged from late October to mid-November during these years. 2019 was the earliest, 2020 was the latest. For the whole population, flowering tended to start a few days before the average plant dates sometime between October and early November. The peak flowering dates, for both individual plants and the population overall, were usually a few days after flowering began. The exact dates varied year to year. For the average plants, the total flowering duration was around 22 to 24 and 8 days with some differences between years.

For the whole population, the duration stayed pretty steady at 33 days each year. The last recorded flowering date was from early November to early December. 2019 had the earliest last flowering, 2021 had the latest. The flowering amplitude - how spread out the flowering was across the population varied year to year. It was the highest in 2021. Flowering synchrony, how synchronized the flowering was in the population, stayed pretty high, mostly above 0.7. This shows a decent amount of synchrony. The percentage of fruits set increased from 2019 to 2022 with 2022 having the highest value (75.55 ± 3.76). This suggests the plants or population got better at reproducing over time and overall, from 2019 to 2022, there was a clear, noteworthy trend of more fruits setting successfully. This key metric shows how well the plants or population reproduced. It steadily increased over the years. In 2022, the fruit set reached a striking peak of $75.55\% \pm 3.76$, indicating that a significant percentage of flowers successfully produced fruit. This big rise over time points to the plants or population improving their ability to reproduce. A noteworthy point to mention is that throughout the study we consistently observed the occurrence of fruit drops. This usually happens in the



Figure 4. 21 Reproductive stages of *P. cerasoides* A: Bud formation, B-C: Anthesis, D: Peak flowering phase, E: Fruit formation, F: Fruit ripening in Mizoram



Figure 4. 22 Reproductive stages of *P. cerasoides* A: Bud formation, B-C: Anthesis, D: Peak flowering phase, E: Fruit formation, F: Fruit ripening in Uttarakhand

middle to part of January although it's important to acknowledge that there can be some variability in the date from year to year.

The findings indicate that flowering timing and duration as fruit set vary from one year to another with some improvement in reproductive success over time. The population shows a level of synchrony in flowering, suggesting that they tend to flower together. Additionally, there is some variation flowering amplitude. The data also consistently demonstrates a pattern where fruit drop occurs every January (Table 4.19, Figure 4.20). The sequential reproductive stages documented in Uttarakhand are illustrated in (Figure 4.22).

The leaf fall in Uttarakhand is observed to start in the last week of September, while in Mizoram, it begins in mid-October. The trees remain leafless throughout the flowering stage, and once the fruits begin to develop, new leaves emerge. These findings demonstrate clear interannual variability in flowering phenology, reproductive success, and associated life cycle events in *P. cerasoides*.

In Mizoram, flowering shows a moderate negative correlation with rainfall ($\rho = -0.426^{**}$, $p < 0.01$). Fruiting also has a moderate negative correlation with rainfall ($\rho = -0.241^{**}$, $p < 0.01$). In contrast, Uttarakhand exhibits a weak negative correlation for flowering with rainfall ($\rho = -0.161^{*}$, $p < 0.05$), while fruiting shows a moderate negative correlation ($\rho = -0.338^{**}$, $p < 0.01$). Regarding humidity, flowering in Mizoram shows a moderate negative correlation ($\rho = -0.293^{**}$, $p < 0.01$). Fruiting also shows a moderate negative correlation with humidity ($\rho = -0.348^{**}$, $p < 0.01$). In contrast, Uttarakhand shows a positive correlation for flowering with humidity ($\rho = 0.225^{**}$, $p < 0.01$), while fruiting exhibits a weak negative correlation and it's not significant ($\rho = -0.100$). When examining maximum temperature, flowering in Mizoram demonstrates a moderate negative correlation ($\rho = -0.287^{**}$, $p < 0.01$). Fruiting also has a moderate negative correlation with maximum temperature ($\rho = -0.285^{**}$, $p < 0.01$). Conversely, in Uttarakhand, flowering shows a moderate positive correlation with maximum temperature ($\rho = 0.360^{**}$, $p < 0.01$), while fruiting does

Table 4. 20 Influence of environmental factors on flowering and fruiting patterns of *P. cerasoides* in Mizoram

		Time	Rainfall (mm)	Humidity (%)	Max.temp (°C)	Min.temp (°C)	Flowering	Fruiting
Time	ρ	1						
	p							
Rainfall (mm)	ρ	-.698**	1					
	p	1.15E-24						
Humidity (%)	ρ	-.649**	.599**	1				
	p	1.61E-20	5.57E-17					
Max.temp(°C)	ρ	-.637**	.485**	.687**	1			
	p	1.34E-19	7.85E-11	1.12E-23				
Min.temp(°C)	ρ	-.849**	.630**	.612**	.281**	1		
	p	1.33E-45	4.55E-19	7.87E-18	0.0003			
Flowering	ρ	0.1161895	-.426**	-.293**	-.287**	-.178*	1	
	p	0.143	1.93E-08	0.0002	0.0002	0.024		
Fruitng	ρ	.336**	-.241**	-.348**	-.285**	-.351**	.433**	
	p	1.43E-05	0.002	6.59E-06	0.0003	5.46E-06	1.04E-08	
**. Correlation is significant at the 0.01 level (2-tailed).								
*. Correlation is significant at the 0.05 level (2-tailed).								

Table 4. 21 Influence of environmental factors on flowering and fruiting patterns of *P. cerasoides* in Uttarakhand

		Time	Rainfall (mm)	Humidity (%)	Max.temp (°C)	Min.temp (°C)	Flowering	Fruiting
Time	ρ	1						
	p							
Rainfall (mm)	ρ	.443**	1					
	p	4.48E-09						
Humidity (%)	ρ	-0.121	.421**	1				
	p	0.127	2.99E-08					
Max.temp (°C)	ρ	-.873**	-.452**	-.185*	1			
	p	3.62E-51	2.01E-09	0.019				
Min.temp (°C)	ρ	-.776**	-.427**	-.274**	.956**	1		
	p	1.86E-33	1.83E-08	0.0005	5.78E-86			
Flowering	ρ	-.542**	-.161*	.225**	.360**	.244**	1	
	p	1.31E-13	0.041	0.004	2.91E-06	0.002		
Fruiting	ρ	-0.103	-.338**	-0.100	0.056	0.132	-0.133	1
	p	0.194	1.20E-05	0.207	0.479	0.097	0.093	

** . Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed).

not exhibit significant correlations. Flowering in Mizoram has a weak negative correlation with minimum temperature ($\rho = -0.178^*$, $p < 0.05$). Fruiting shows a moderate negative correlation with minimum temperature ($\rho = -0.351^{**}$, $p < 0.01$). In contrast, Uttarakhand displays a moderate positive correlation for flowering with minimum temperature ($\rho = 0.244^{**}$, $p < 0.01$), while fruiting does not show significant correlations. (Table 4.20) (Table 4.21).

4.7 Pollen viability, effect of growth hormones on *in vitro* pollen germination

Pollen viability of *P. cerasoides* was evaluated using the TTC test (Figure 4.23). In Uttarakhand, pollen grains collected at the pre-anthesis stage (unopened flower) exhibited a viability of 52.29 ± 5.78 , while those at anthesis showed increased viability at 66.42 ± 5.51 . Similarly, in Mizoram, viability at the pre-anthesis stage was 28.05 ± 4.61 , rising to 56.81 ± 4.70 during anthesis. These results indicate that pollen viability is consistently higher during the anthesis stage at both study sites, highlighting this phase as the optimal period for pollination (Figure 4.24).

In both research locations, *in vitro* pollen grain germination responded differently to several growth regulators (IAA, IBA, GA3, and Kinetin), sucrose concentrations, and timeframes. In the first 24 hours, 1.32 ± 0.78 and 1.87 ± 0.75 , respectively, for Mizoram and Uttarakhand, were the low percentages of pollen germination detected in both research locations; after 48 hours, 1.14 ± 0.59 and 1.19 ± 0.49 were noted. At 72 hours, there was poor pollen germination for both study sites (0.34 ± 0.22 ; 0.66 ± 0.19) in the distilled water (control). It was shown that sucrose concentrations of 5% and 10% acted as a fundamental substrate and induced *in vitro* pollen germination in comparison to the control. At a sucrose concentration of 5%, Mizoram demonstrated low pollen germination at $2.13 \pm 0.42\%$, while Uttarakhand showed fair germination in the first 24 hours at $3.14 \pm 1.22\%$. Mizoram demonstrated low germination at $2.65 \pm 0.57\%$ at a 10% sucrose concentration. Moreover, the germination percentage reduced in comparison between 48 and 72 hours (Figure 4.25 and Figure 4.26).

In Uttarakhand, the ANOVA results revealed that the effect of treatment was not statistically significant ($F = 1.79$, $p = 0.173$), indicating no substantial difference between distilled water and sucrose treatments at 5% and 10%. However,



Figure 4. 23 Pollen viability of (a) Uttarakhand and (b) Mizoram tested with TTC, red stained pollen grains are viable

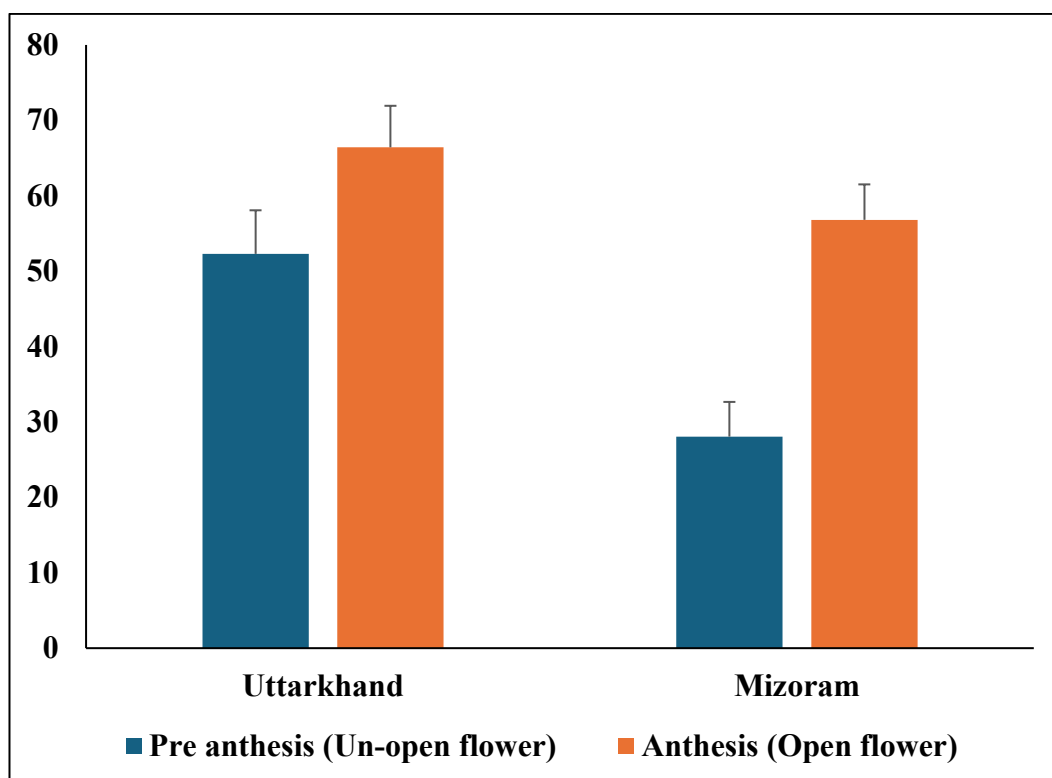


Figure 4. 24 Pollen viability tested with TTC in *P. cerasoides* (Uttarakhand and Mizoram)

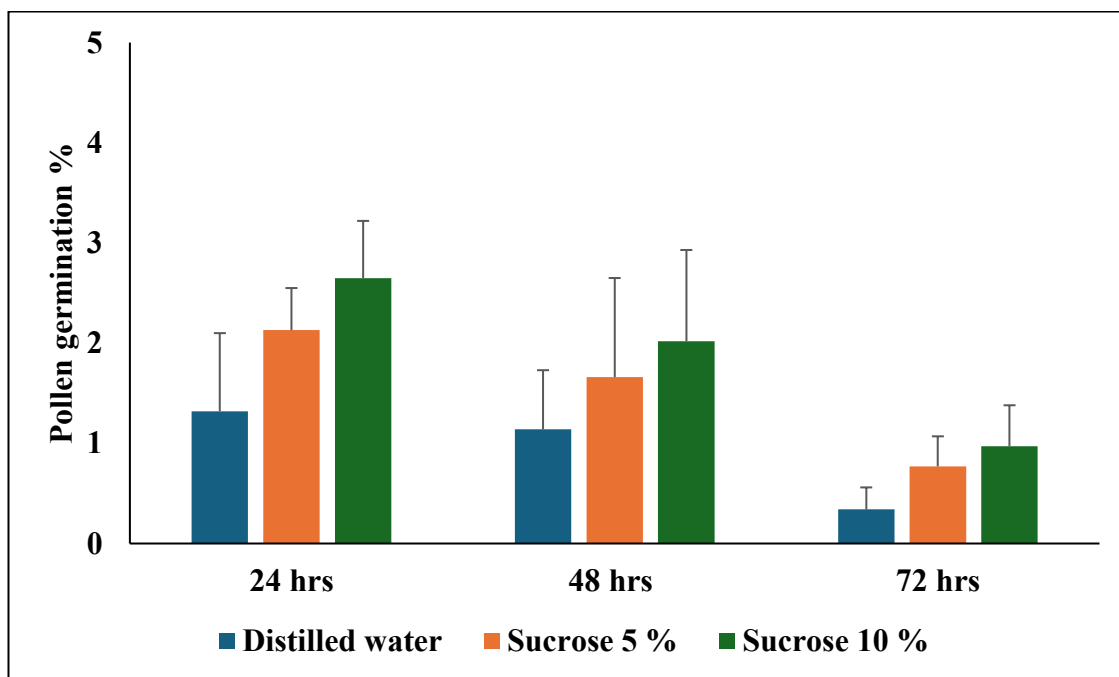


Figure 4. 25 Influence of distilled water and sucrose at 5% & 10% on *in vitro* pollen germination (Mizoram)

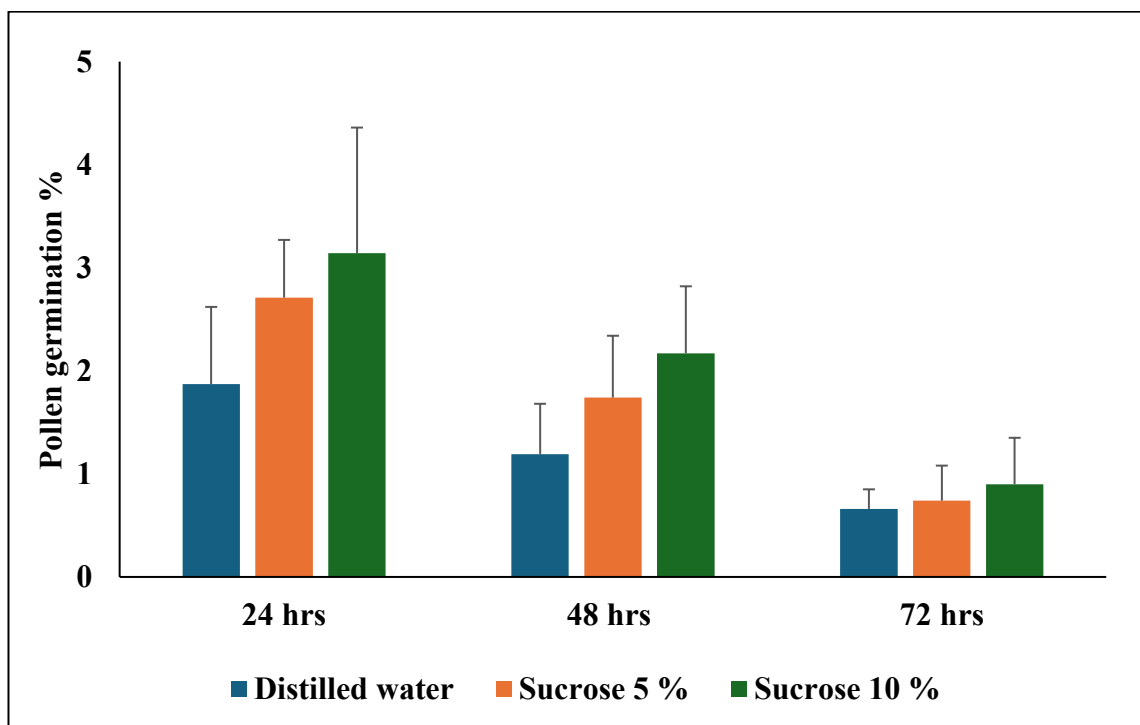


Figure 4. 26 Influence of distilled water and sucrose at 5% & 10% on *in vitro* pollen germination (Uttarakhand)

Table 4. 22 ANOVA for distil water and sucrose 5% and 10%, concentration and time

Uttarakhand	Treatment	SS	df	MS	F	p
	Between dist. water and sucrose 5% & 10%	54.87320867	2	27.4366	1.79344	0.172698643
	Concentration	2068.531417	2	1034.27	9.7855	0.000780126
	Time	40.41822086	2	20.2091	0.89888	0.410902357
Mizoram	Between dist. water and sucrose 5% & 10%	64.05165198	2	32.0258	1.62836	0.202384942
	Concentration	149.6880393	2	74.844	0.75199	0.482215638
	Time	210.8104179	2	105.405	1.93113	0.151366145

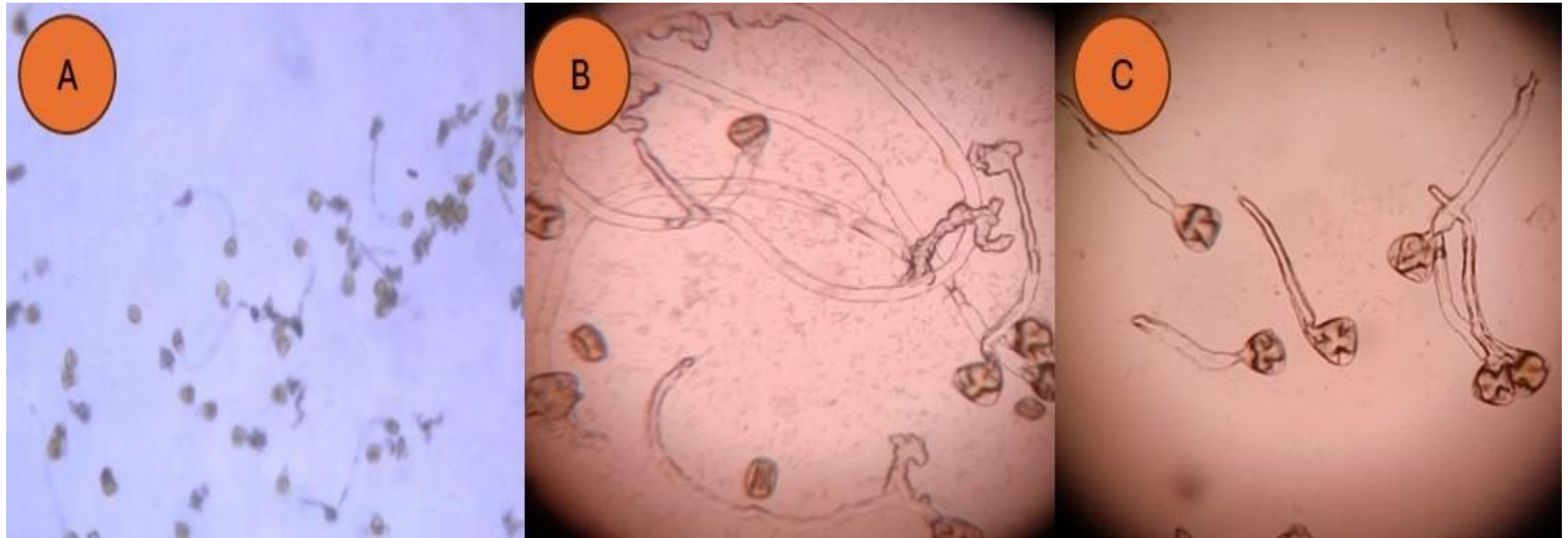


Figure 4. 27 *In vitro* pollen germination of *P. cerasoides*; A pollen grain was considered germinated when the length of the pollen tube was $\geq$ than the diameter of the pollen grain

concentration had a highly significant effect on the measured outcome ($F = 9.79$, $p < 0.001$), suggesting that variation in sucrose concentration played a decisive role in influencing the response variable. In contrast, time did not exhibit a significant effect ($F = 0.90$, $p = 0.411$), indicating that the duration of the treatment did not notably affect the results in this region. In Mizoram, none of the examined factors were found to have a statistically significant effect on the measured parameter, with treatment ($F = 1.63$, $p = 0.202$), concentration ($F = 0.75$, $p = 0.482$), and time ($F = 1.93$, $p = 0.151$) all yielding non-significant results. (Table 4.22).

In vitro pollen germination was observed in *P. cerasoides* samples from both Mizoram and Uttarakhand, with germination recorded only when the pollen tube length exceeded the diameter of the pollen grain (Tuinstra and Wedel, 2000). Germinated grains exhibited clear pollen tube elongation, as shown in the representative image (Figure 4.27). The germination response varied under different growth hormone treatments. All four hormones, GA₃, kinetin, IBA, and IAA had measurable effects on pollen germination, though their influence differed across treatments.

In Mizoram, the effects of different concentrations of growth hormones (IAA, IBA, GA₃, and kinetin), each supplemented with 10% sucrose, were evaluated on *in vitro* pollen germination over three-time intervals (24, 48, and 72 hours). Overall, *in vitro* pollen germination percentages declined progressively over time for all hormone treatments, with the highest germination typically observed at 24 hours and decreasing thereafter. Among the treatments, gibberellic acid (GA₃) at 100 mg L⁻¹ exhibited the highest pollen germination percentage ($8.71 \pm 1.24\%$) at 24 hours, indicating a strong promotive effect at this concentration and time point. This was followed by kinetin at 100 mg L⁻¹ ($6.37 \pm 1.73\%$) and indole-3-butyric acid (IBA) at 100 mg L⁻¹ ($3.18 \pm 0.94\%$). Indole-3-acetic acid (IAA) exhibited consistently low *in vitro* pollen germination across all tested concentrations 100 mg L⁻¹, 200 mg L⁻¹, and 300 mg L⁻¹ with the highest germination recorded at only $1.87 \pm 0.84\%$ at 100 mg L⁻¹ after 24 hours. For all hormones, increasing concentrations were generally associated with a reduction in pollen germination. At 24 hours, GA₃ at 300 mg L⁻¹ resulted in a notably

lower *in vitro* pollen germination percentage 2.63 ± 0.80 compared to 8.71 ± 1.24 observed at 100 mg L^{-1} . A similar trend was observed with kinetin, where germination decreased from 6.37 ± 1.73 at 100 mg L^{-1} to 3.45 ± 1.16 at 300 mg L^{-1} . A consistent pattern of decreasing pollen germination over time was evident, with minimal germination observed at 72 hours across all treatments (Table 4.23).

The influence of four growth hormones, indole-3-acetic acid (IAA), indole-3-butyric acid (IBA), gibberellic acid (GA_3), and kinetin, each supplemented with 10% sucrose, was assessed in samples from Uttarakhand at three concentrations (100 mg L^{-1} , 200 mg L^{-1} , and 300 mg L^{-1}) over incubation periods of 24, 48, and 72 hours to determine their effects on *in vitro* pollen germination. Overall, pollen germination was highest at 24 hours for all treatments and declined progressively over time, indicating a temporal reduction in germination viability. Among the hormones tested, GA_3 at 100 mg L^{-1} resulted in the highest germination percentage (9.15 ± 3.52) at 24 hours. This was followed by kinetin (7.54 ± 1.66) and IBA (3.77 ± 0.99) at the same concentration, suggesting that GA_3 and kinetin at lower concentrations are particularly effective in promoting early pollen germination. Notably, GA_3 maintained relatively consistent germination across time intervals, with 2.27 ± 0.94 still observed at 200 mg L^{-1} after 72 hours, indicating its comparatively prolonged stimulatory effect.

In contrast, IAA exhibited consistently low germination percentages across all concentrations tested (100 mg L^{-1} , 200 mg L^{-1} , and 300 mg L^{-1}), with a maximum of 2.19 ± 0.92 recorded at 100 mg L^{-1} after 48 hours. Similarly, increased concentrations of all hormones (300 mg L^{-1}) generally led to diminished germination rates, implying possible inhibitory effects at higher doses. For instance, kinetin and IBA at 300 mg L^{-1} resulted in very low germination percentages at 72 hours (0.34 ± 0.18 and 0.00 ± 0.00 , respectively). GA_3 and kinetin, particularly at 100 mg L^{-1} , were the most effective in enhancing *in vitro* pollen germination under the experimental conditions (Table 4.24).

The analysis of variance (ANOVA) results for the effects of growth hormones, concentration, and time on *in vitro* pollen germination in Uttarakhand and Mizoram showed notable differences between the two regions. In Uttarakhand, the hormone

Table 4. 23 Effect of growth hormones on *in vitro* pollen germination% (Mizoram)

Growth hormones	Concentrations	Pollen germination %		
		24 hrs	48 hrs	72 hrs
IAA (10 % Sucrose)	100 mg L ⁻¹	1.87±0.84	1.01±0.36	0.61±0.29
	200 mg L ⁻¹	1.28±0.60	0.86±0.50	0.56±0.18
	300 mg L ⁻¹	0.68±0.37	0.53±0.18	0.49±0.35
IBA (10 % Sucrose)	100 mg L ⁻¹	3.18±0.94	1.80±0.46	1.02±0.48
	200 mg L ⁻¹	2.36±0.62	1.13±0.48	0.81±0.36
	300 mg L ⁻¹	2.70±1.04	1.07±0.62	0.53±0.27
GA ₃ (10 % Sucrose)	100 mg L ⁻¹	8.71±1.24	2.21±1.37	1.16±0.91
	200 mg L ⁻¹	3.94±1.68	1.09±0.46	1.01±0.62
	300 mg L ⁻¹	2.63±0.80	1.04±0.47	0.71±0.16
Kinetin (10 % Sucrose)	100 mg L ⁻¹	6.37±1.73	1.79±0.68	0.72±0.29
	200 mg L ⁻¹	4.31±0.88	1.28±0.84	0.55±0.24
	300 mg L ⁻¹	3.45±1.16	1.05±0.52	0.62±0.30

Table 4. 24 Effect of growth hormones on *in vitro* pollen germination (Uttarakhand)

Growth hormones	Concentrations	Pollen germination %		
		24 hrs	48 hrs	72 hrs
IAA (10% Sucrose)	100 mg L ⁻¹	1.46±0.80	2.19±0.92	0.90±0.39
	200 mg L ⁻¹	1.08±0.60	1.06±0.52	0.71±0.58
	300 mg L ⁻¹	1.48±0.88	1.04±0.58	0.61±0.32
IBA (10% Sucrose)	100 mg L ⁻¹	3.77±0.99	2.59±1.49	1.91±0.97
	200 mg L ⁻¹	3.15±0.93	1.22±0.91	0.42±0.25
	300 mg L ⁻¹	2.45±0.56	1.07±0.65	0.00±0.00
GA3 (10% Sucrose)	100 mg L ⁻¹	9.15±3.52	5.95±1.42	2.21±0.86
	200 mg L ⁻¹	3.76±1.85	1.56±0.92	2.27±0.94
	300 mg L ⁻¹	1.33±0.49	1.28±0.85	2.20±1.43
Kinetin (10% Sucrose)	100 mg L ⁻¹	7.54±1.66	5.84±0.82	1.01±0.37
	200 mg L ⁻¹	4.14±1.55	3.21±0.95	0.20±0.05
	300 mg L ⁻¹	3.77±0.77	1.25±0.44	0.34±0.18

Table 4. 25 ANOVA for the effect of hormones, concentrations and time

Study Site	Treatment	SS	df	MS	F	p
Uttarkhand	Hormone	342.346	3	114.115	1.23853	0.29919
	Concentration	509.775	2	254.887	2.75996	0.06753
	Time	928.016	2	464.008	7.29096	0.00079
	Hormone*concentration	969.132	6	161.522	1.89245	0.08857
	Concentration*time	186.054	6	31.0089	1.76852	0.10467
	Hormone*time	364.664	6	60.7774	0.98649	0.43417
Mizoram	Hormone	134.5	3	44.8334	3.57973	0.01629
	Concentration	109.982	2	54.9908	4.44803	0.0138
	Time	87.4058	2	43.7029	3.85445	0.02208
	Hormone*concentration	171.54	6	28.5901	2.6771	0.01842
	Concentration*time	126.755	6	21.1259	6.51949	1.6E-06
	Hormone*time	5.50521	6	0.91754	0.08849	0.99741

treatments did not significantly affect pollen germination, as evidenced by the p-value of 0.29919 ($F = 1.23853$). This suggests that the different hormones tested did not have a strong influence on pollen germination in this region. Concentration, while showing a marginally significant effect ($p = 0.06753$, $F = 2.75996$), did not reach the conventional significance threshold of 0.05, indicating that hormone concentration had a weak impact on germination. Time, however, had a significant effect on pollen germination ($p = 0.00079$, $F = 7.29096$), indicating that the duration of exposure to the growth hormones played a critical role in modulating germination. The interaction between hormone and concentration ($p = 0.08857$, $F = 1.89245$), concentration and time ($p = 0.10467$, $F = 1.76852$), and hormone and time ($p = 0.43417$, $F = 0.98649$) were all not significant in Uttarakhand, suggesting that these combined factors did not substantially influence pollen germination. In contrast, in Mizoram, hormone treatments had a significant effect on pollen germination ($p = 0.01629$, $F = 3.57973$). Concentration also significantly affected germination ($p = 0.0138$, $F = 4.44803$), emphasizing the role of hormone concentration in modulating the process. Time was another significant factor in Mizoram, with a p-value of 0.02208 ($F = 3.85445$). The interaction between hormone and concentration was significant ($p = 0.01842$, $F = 2.6771$). The interaction between concentration and time was highly significant ($p = 1.6E-06$, $F = 6.51949$). However, the interaction between hormone and time was not significant ($p = 0.99741$, $F = 0.08849$), indicating that the timing of hormone application did not alter its impact on germination in Mizoram (Table 4.25)

4.8 The pollinators availability in *P. cerasoides* for Mizoram (2019)

In 2019, *P. cerasoides* attracted a range of pollinators, including birds, bees, wasps, hornets, butterflies, and squirrels. A total of seven bird species were recorded visiting its flowers: *Zosterops palpebrosus* Temminck, *Pycnonotus cafer* Linnaeus, *Phylloscopus pulcher* Blyth, *Aethopyga gouldiae* Vigors, *Horornis brunnescens* Hume, *Orthotomus sutorius* Linnaeus and *Arachnothera longirostra* Latham. Among hymenopterans, *Apis cerana* Fabricius, *Vespa velutina* Lepeletier, and *Delta esuriens* Fabricius were observed. Additionally, seven lepidopteran species *Delias descombesi* Boisduval, *Delias acalis* Godart, *Delias pasithoe* Linnaeus, *Appias olferna* Swainson, *Delias hyparete* Linnaeus, *Pantoporia hordonia* Stoll and *Vindula erota* Fabricius were found interacting with the flowers. The squirrel *Callosciurus pygerythrus* I. Geoffroy Saint Hilaire was also documented as a floral visitor (Figure 4.28).

Bird activity was recorded throughout the day, with the highest visitation between 10:00 A.M. and 12:00 p.m. *Pycnonotus cafer* showed the highest visitation rate, followed by *Zosterops palpebrosus*, *Phylloscopus pulcher*, *Arachnothera longirostra*, *Horornis brunnescens*, and *Orthotomus sutorius* (Figure 4.29). *Apis cerana* exhibited diurnal activity, peaking between 10:00 A.M. to 12:00 P.M. and around 2:00 P.M. *Vespa velutina* showed consistent diurnal visits, while *Delta esuriens* was active in both morning and afternoon. No visits by these hymenopterans were observed during nighttime hours (Figure 4.30).

Among butterflies, *Delias descombesi* had the highest visitation, followed by *Delias acalis*, *Delias pasithoe*, *Appias olferna*, *Delias hyparete*, *Pantoporia hordonia*, and *Vindula erota* (Figure 4.31). *Callosciurus pygerythrus* (Squirrel) visitation was steady throughout the morning and afternoon, with the highest activity observed from 10:00 A.M. to 12:00 P.M. Notably, no visits were recorded between 6:00 A.M. to 8:00 A.M. and 4:00 P.M. to 6:00 P.M. (Figure 4.32).

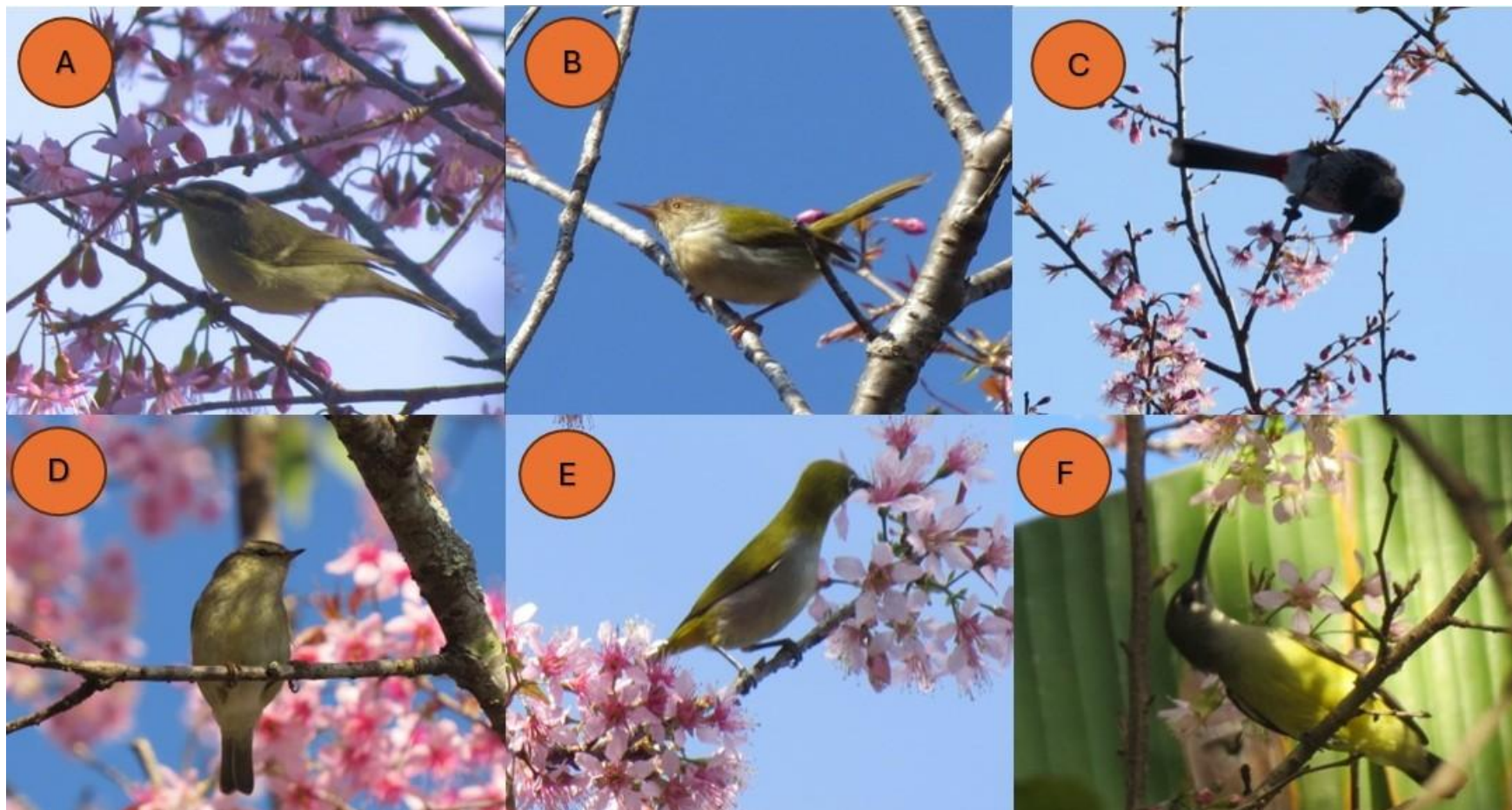


Figure 4. 28 Pollinators of Mizoram

(A) *Orthotomus sutoris* (B) *Phylloscopus pulcher* (C) *Pycnonotus cafer* (D) *Horornis brunnescens* (E) *Zosterops palpebrosus* (F) *Arachnothera longirostra*

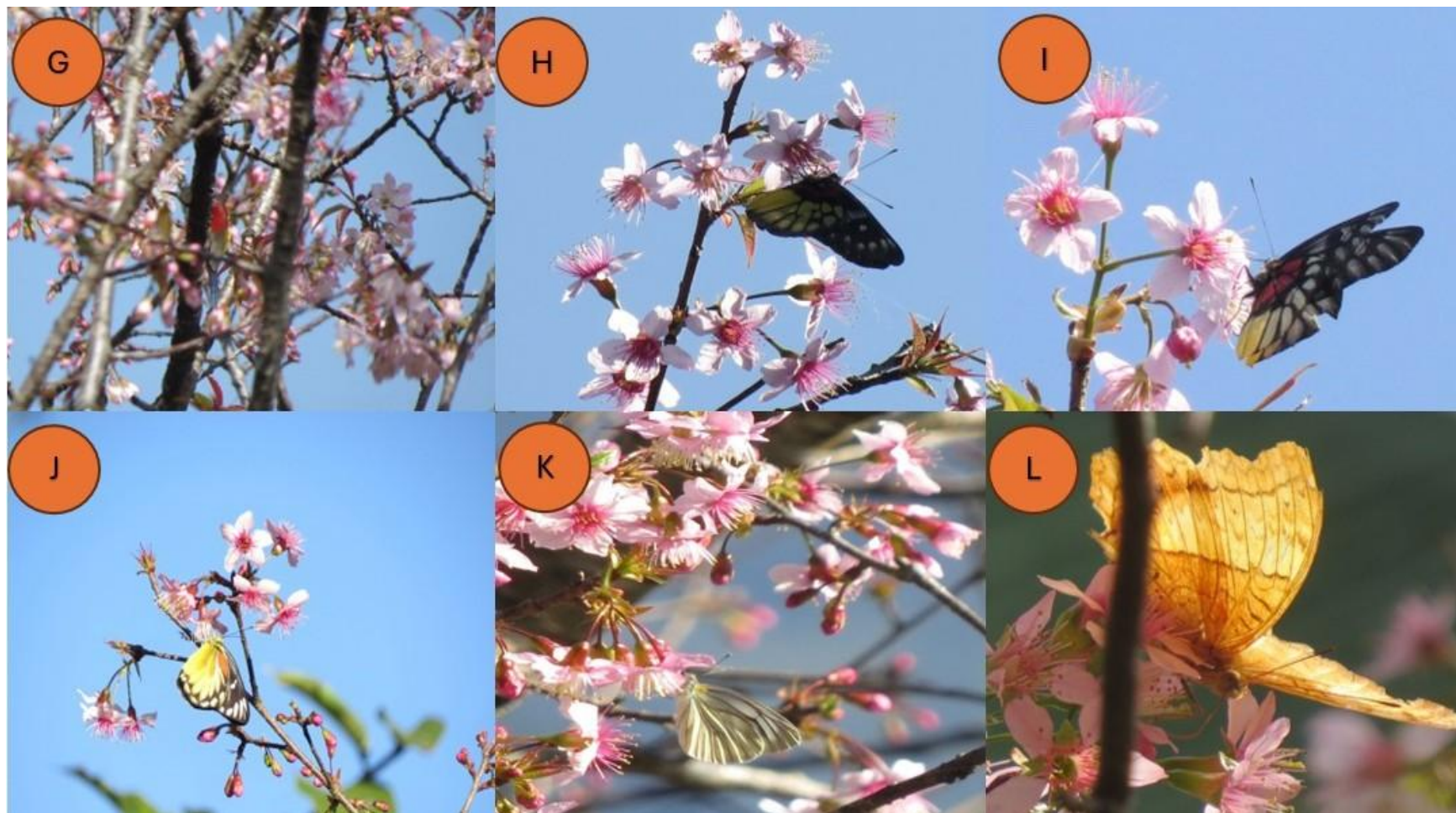


Figure 4. 29 Pollinators of Mizoram

(G) *Aethopyga gouldiae* (H) *Delias acalis* (I) *Delias pasithoe* (J) *Delias descombesi* (K) *Appias olferna* (L) *Vindula erota*



Figure 4. 30 Pollinators of Mizoram

(M) *Delias hyparete* (N) *Pantoporia hordonia* (O) *Apis cerana* (P) *Vespa velutina* (Q) *Delta esuriens* (R) *Callosciurus pygerythrus*

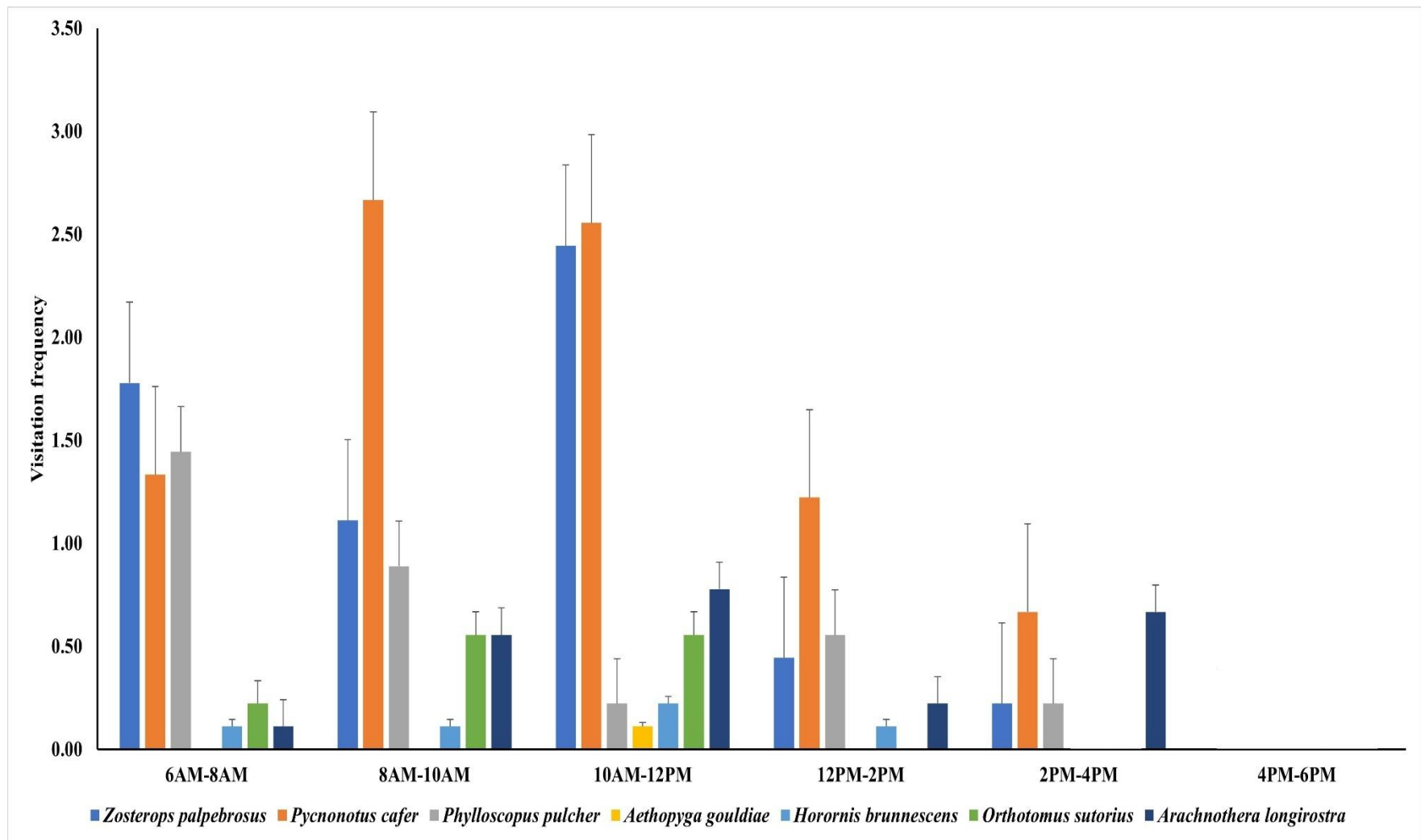


Figure 4. 31 Visitation frequency of birds in Mizoram, 2019 (N= 10 trees, Mean $\pm$ SE)

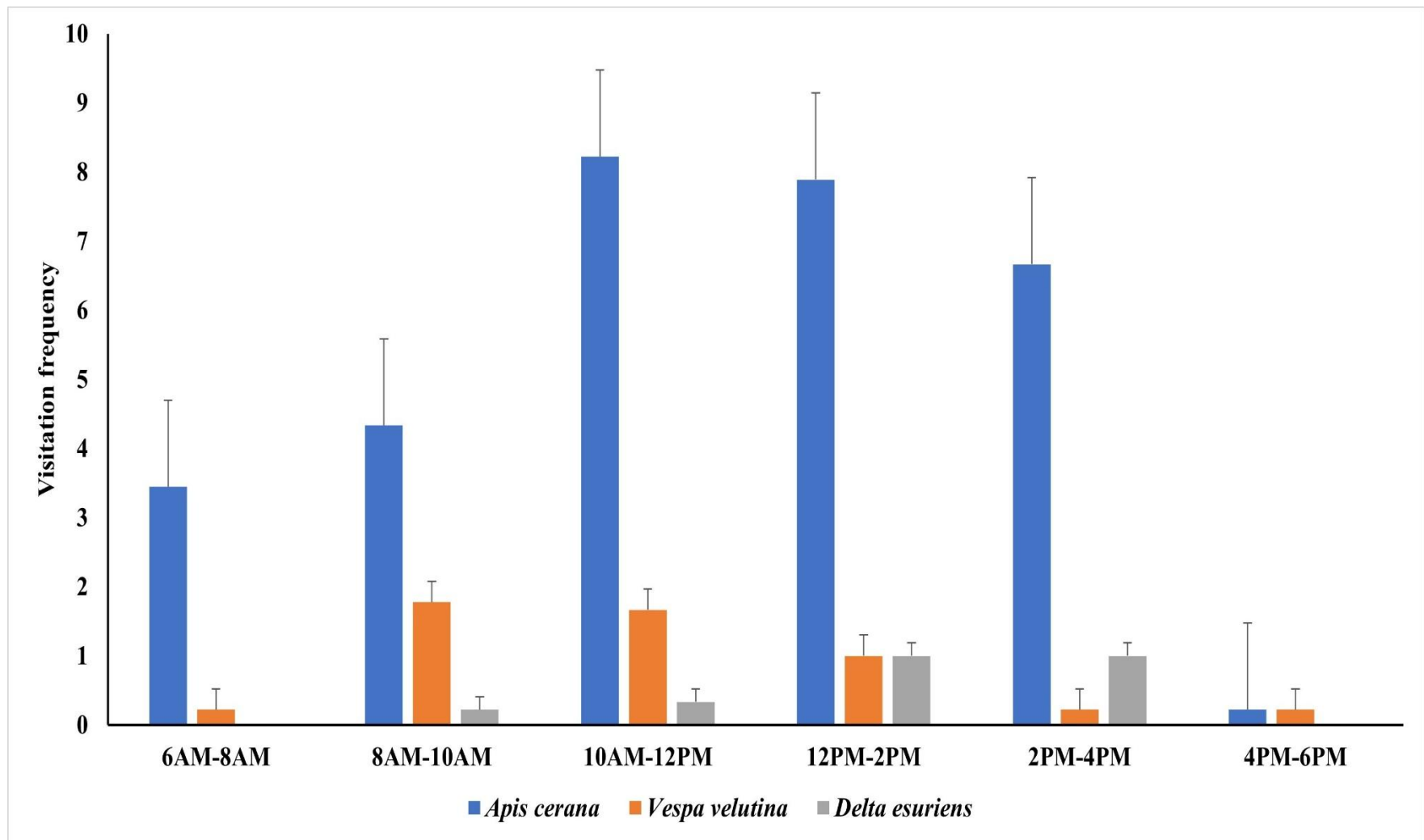


Figure 4. 32 Visitation frequency of bees, wasps and hornets in Mizoram, 2019 (N= 10 trees, Mean $\pm$ SE)

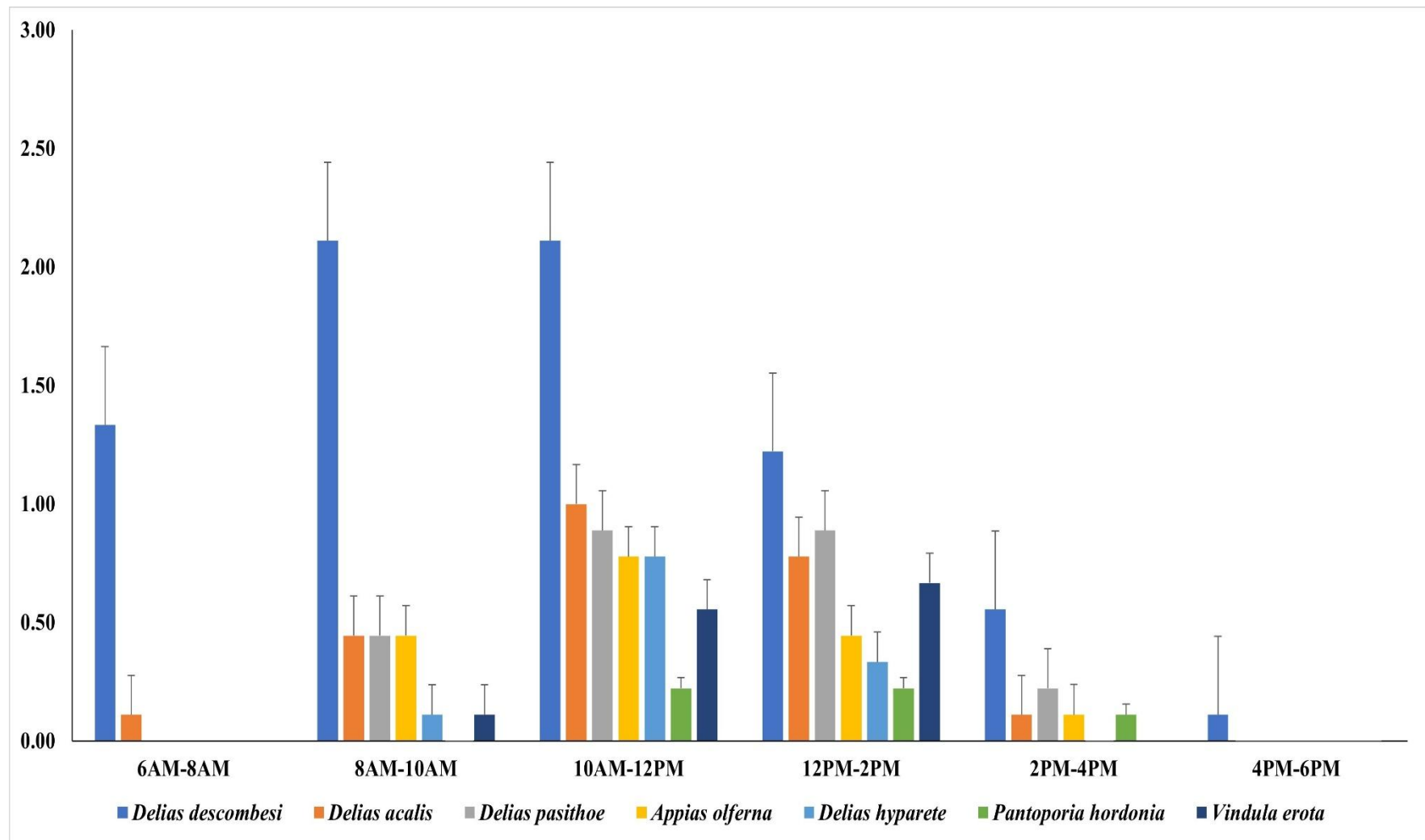


Figure 4. 33 Visitation frequency of butterflies in Mizoram, 2019 (N= 10 trees, Mean $\pm$ SE)

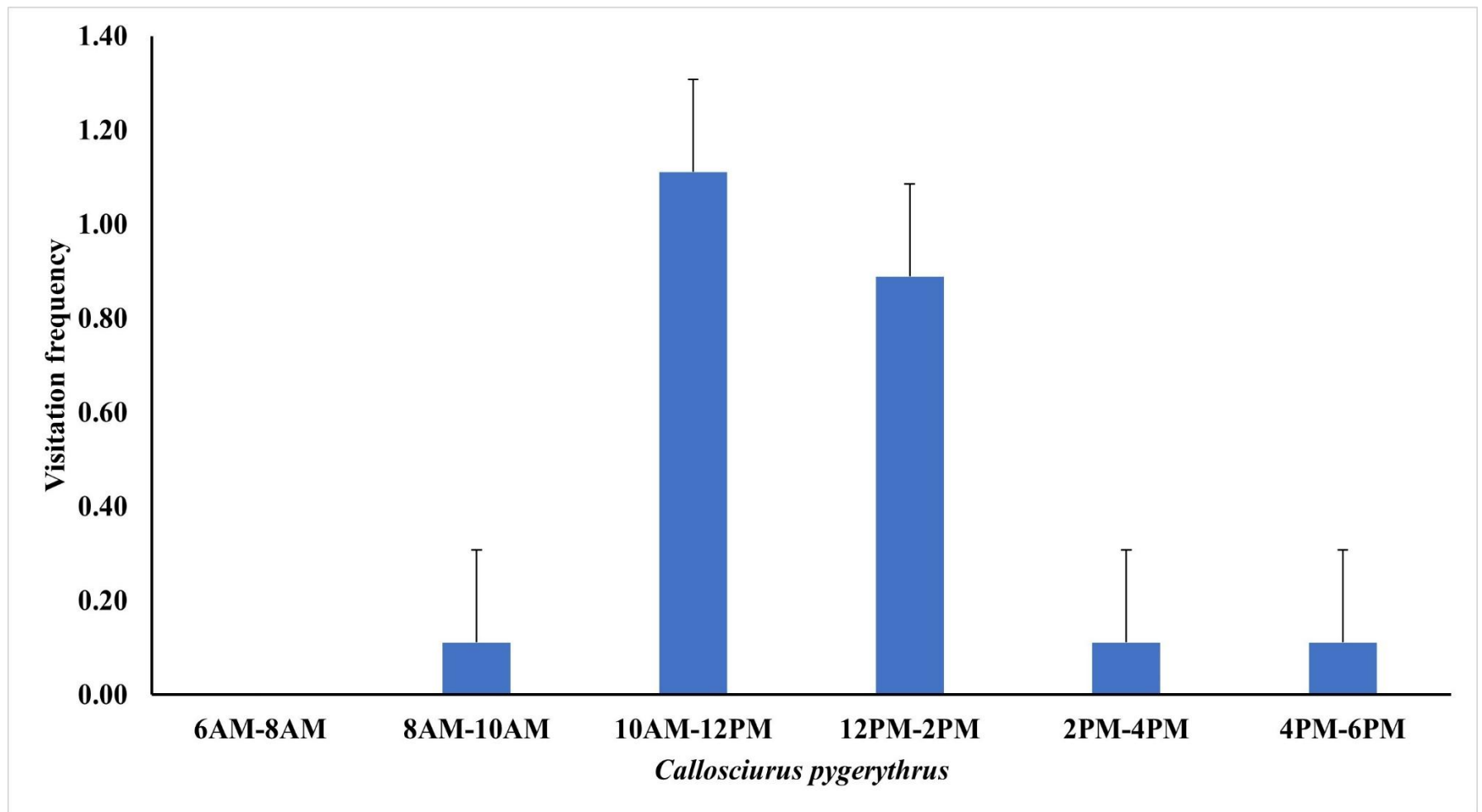


Figure 4. 34 Visitation frequency of squirrel in Mizoram, 2019 (N= 10 trees, Mean $\pm$ SE)

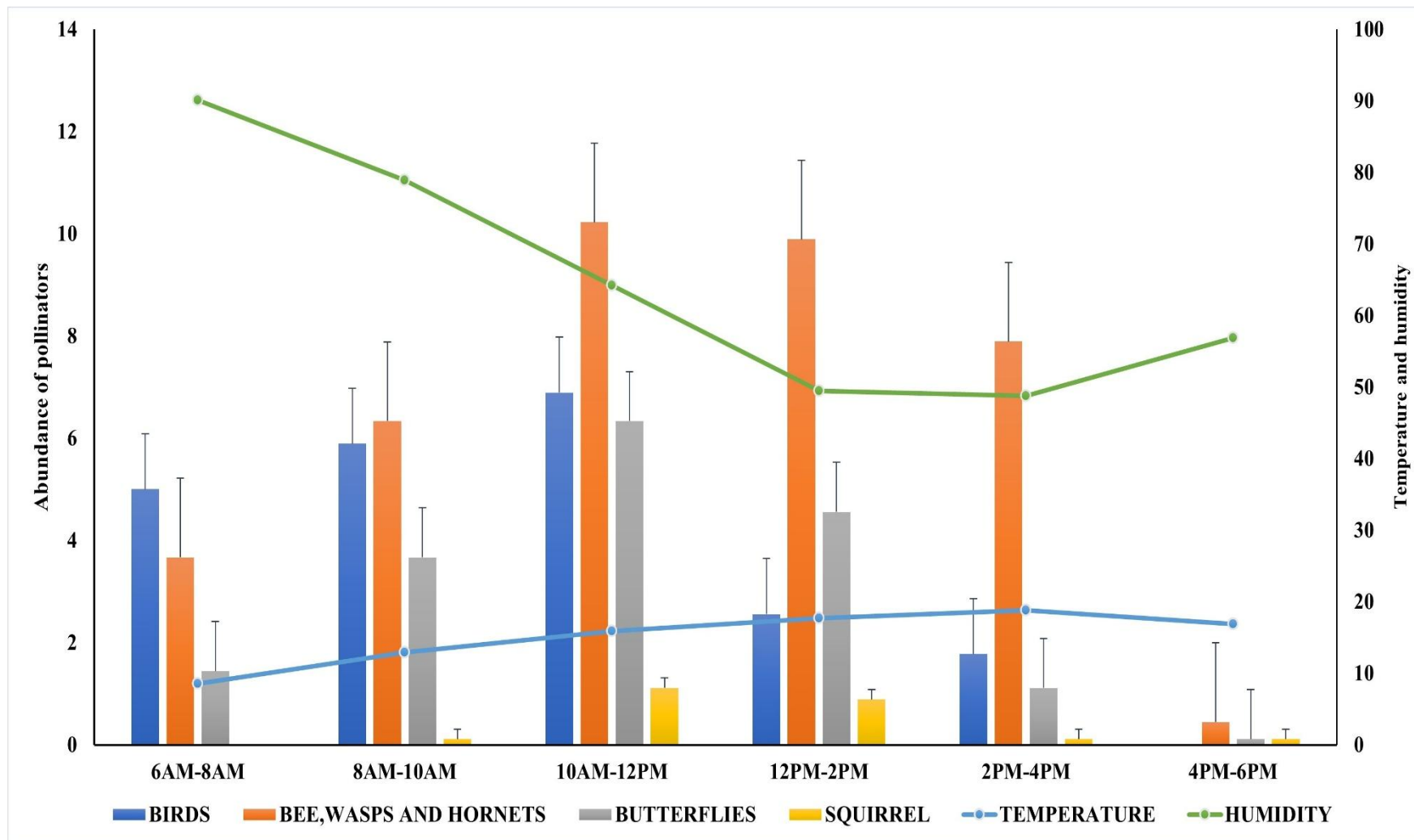


Figure 4. 35 Abundance of pollinators with respect to time, temperature and humidity, Mizoram, 2019 (N= 10 trees, Mean $\pm$ SE)

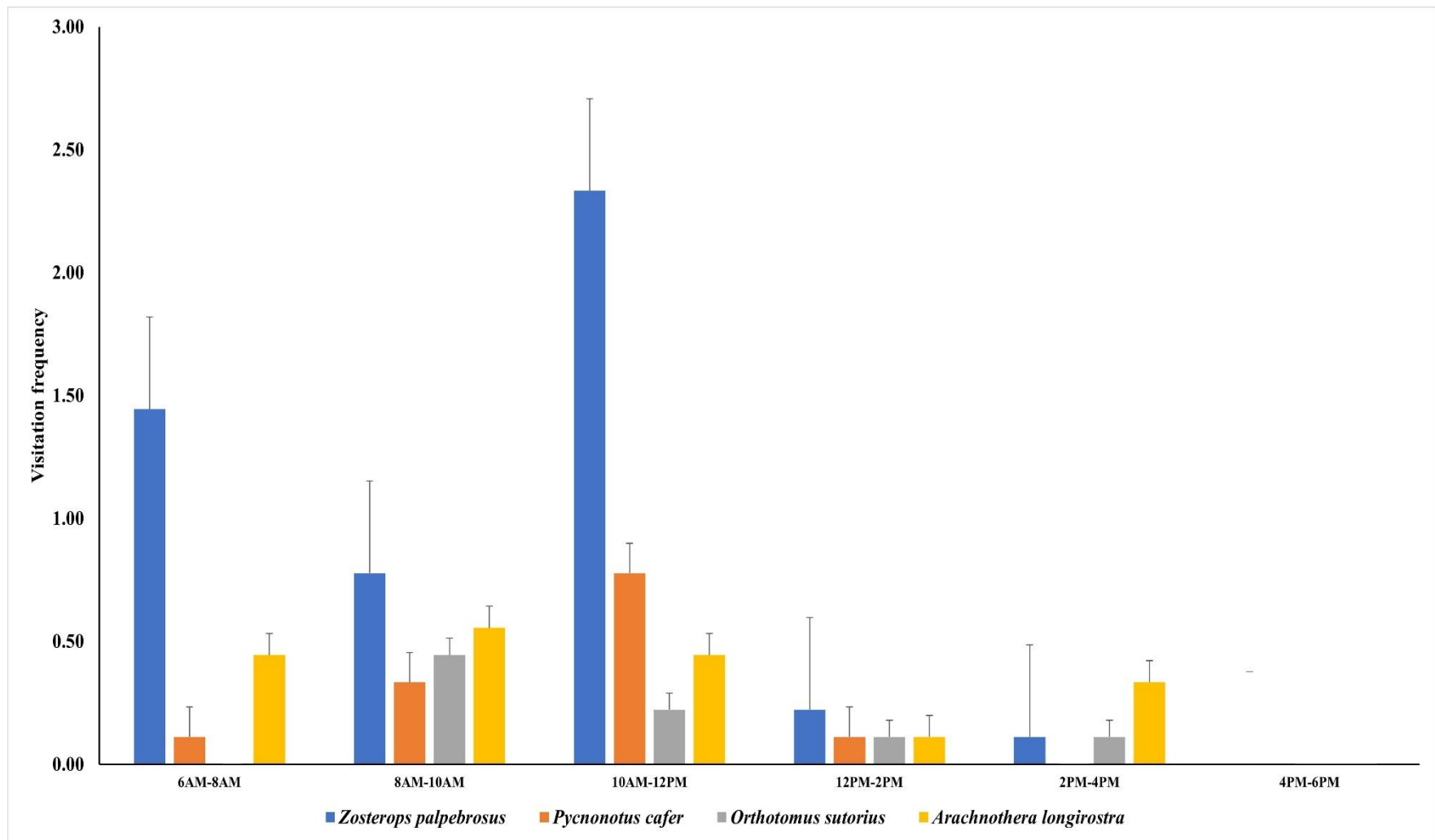


Figure 4. 36 Visitation frequency of birds in Mizoram, 2021 (N= 10 trees, Mean $\pm$ SE)

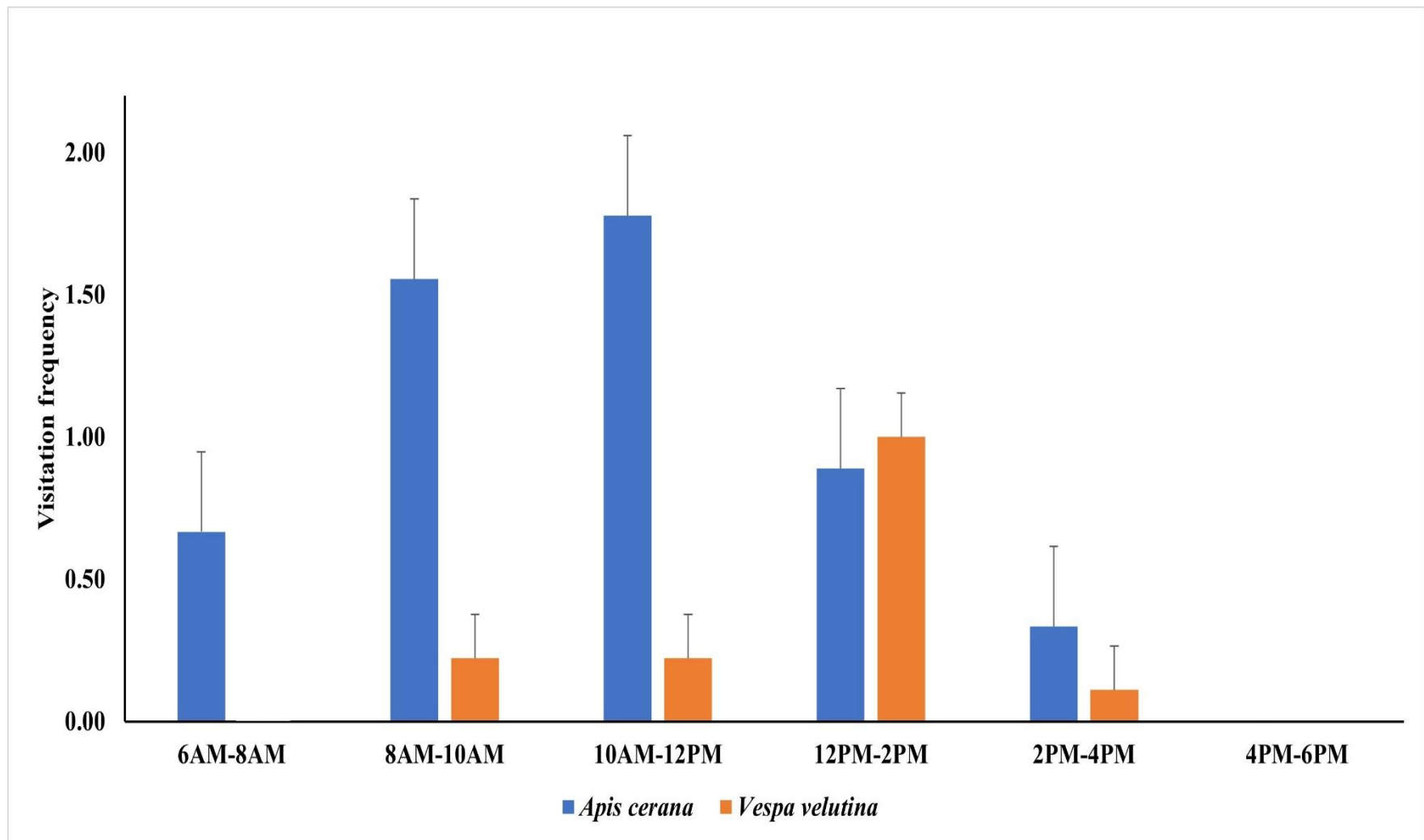


Figure 4. 37 Visitation frequency of bees and hornets in Mizoram, 2021 (N= 10 trees, Mean $\pm$ SE)

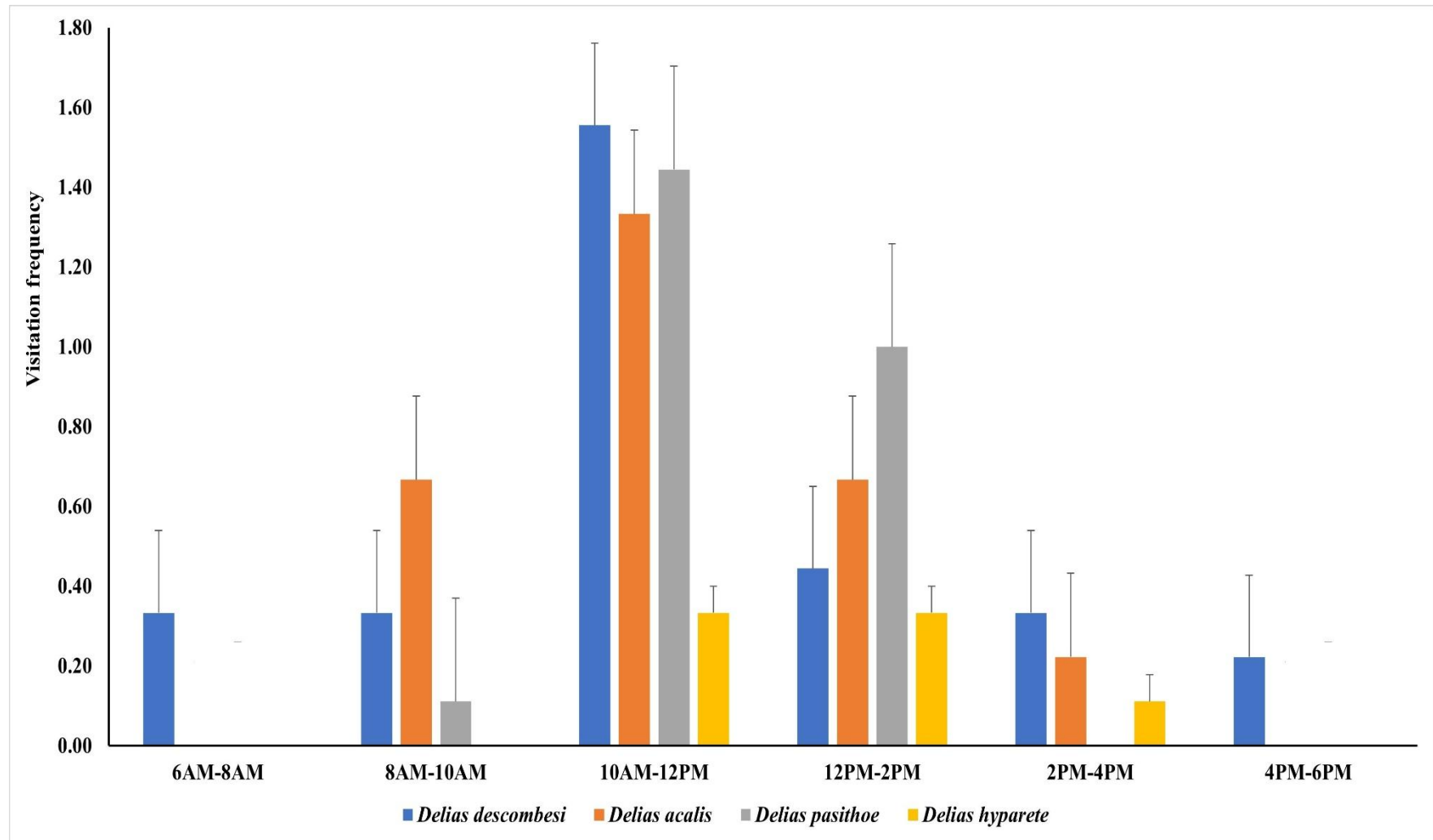


Figure 4. 38 Visitation frequency of butterflies in Mizoram, 2021 (N= 10 trees, Mean $\pm$ SE)

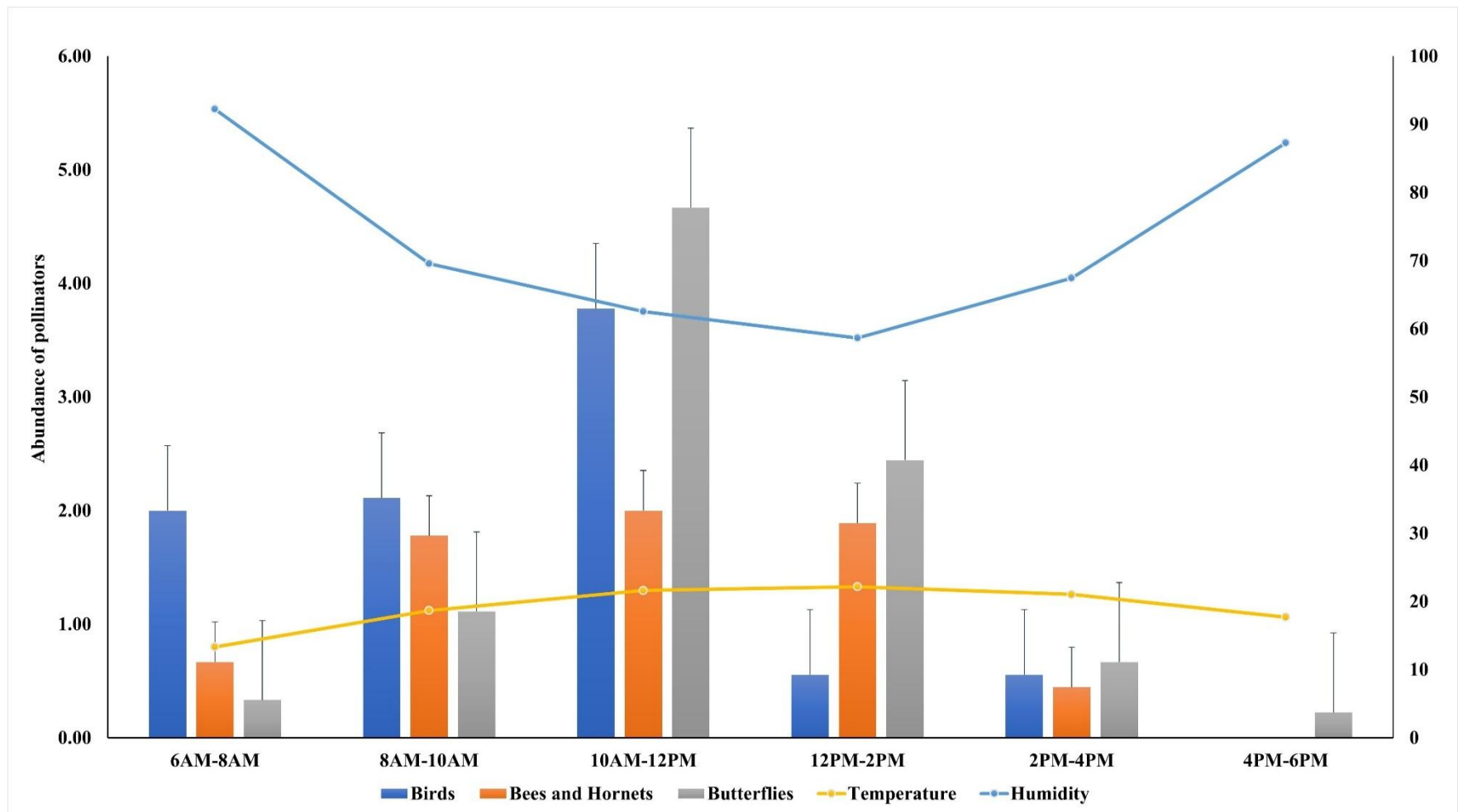


Figure 4. 39 Abundance of pollinators in Mizoram with respect to time, temperature and humidity, Mizoram, 2021 (N= 10 trees, Mean $\pm$ SE)

Pollinator visitation frequency was influenced by time, temperature, and humidity. A rise in temperature generally corresponded with increased visitation rates. Bird visits increased with rising temperature and declined as it dropped. Bees, wasps, and hornets also showed higher activity during warmer periods, with reduced visitation in cooler hours. Butterfly visits peaked between 10:00 A.M. and 12:00 A.M. aligning with higher temperature, while activity declined as the temperature fell. *Callosciurus pygerythrus* responded similarly, with peak visits between 10:00 A.M. and 12:00 P.M. (Figure 4.33).

4.9 The pollinators availability in *P. cerasoides* for Mizoram (2021)

In 2021, four avian species were recorded visiting *P. cerasoides* in Mizoram. Among them, *Zosterops palpebrosus* was observed at the highest elevation, followed by *Arachnothera longirostra*, *Pycnonotus cafer*, and *Orthotomus sutorius* (Figure 4.28). Bird visitation was recorded throughout the day, with the highest frequency observed between 10:00 A.M. and 12:00 P.M. (Figure 4.34).

Apis cerana displayed consistent floral visitation during daylight hours, with peak activity occurring from 10:00 A.M. to 12:00 P.M. No activity was recorded between 4:00 P.M. and 6:00 P.M. In contrast, *Vespa velutina* showed peak visitation between 12:00 P.M. and 2:00 P.M., with no visits recorded during 6:00–8:00 A.M. or 4:00–6:00 P.M. (Figure 4.35).

The flowers of *P. cerasoides* attracted four butterfly species. Among them, *Delias descombesi* had the highest visitation rate, followed by *Delias acalis*, *Delias pasithoe*, and *Delias hyparete*. Visitation was noted at various times throughout the day, with peak activity between 10:00 A.M. and 12:00 P.M. (Figure 4.36).

Pollinator activity overall was highest when temperatures rose, particularly from 10:00 A.M. to 12:00 P.M. A drop in temperature corresponded with reduced activity,

especially among birds, bees, and hornets. Butterflies, however, were observed visiting flowers steadily throughout the day (Figure 4.37).

4.10 The pollinators availability in *P. cerasoides* for Uttarakhand (2019)

During the 2019 study period in Uttarakhand, four distinct categories of pollinators were observed visiting *P. cerasoides*. Among the avian visitors documented were *Argya striata* Dumont, *Passer cinnamomeus* Linnaeus, *Passer domesticus* Linnaeus, *Machlolophus xanthogenys* Vigors, *Parus monticolus* Walden, *Aegithalos concinnus* Horsfield, and *Zosterops palpebrosus* Temminck (Figure 4.38).

Notably, no bird visitation was recorded between 4:00 p.m. and 6:00 p.m. The data indicate that the highest frequency of bird visitation occurred between 8:00 a.m. and 10:00 a.m., as illustrated (Figure 4.39).

In the hymenopteran group, *Vespa basalis* Smith exhibited visitation activity during two primary intervals: 8:00 a.m. to 10:00 a.m. and 10:00 a.m. to 12:00 p.m. No visits were recorded during the nighttime hours. *Bombus haemorrhoidalis* Smith was observed actively foraging throughout most of the day, except during 6:00 a.m. to 8:00 a.m. and 4:00 p.m. to 6:00 p.m., during which no visitation activity was documented. The highest frequency of bumblebee visitation occurred between 8:00 a.m. and 10:00 a.m. (Figure 4.40).

Three butterfly species were recorded: *Aglais caschmirensis* Kollar, *Vanessa indica* Herbst, and *Gonepteryx rhamni* Linnaeus. Visitation activity by butterflies was generally low. Notably, no butterfly visits were observed during the time intervals of 6:00 a.m. to 8:00 a.m., 8:00 a.m. to 10:00 a.m., or 4:00 p.m. to 6:00 p.m. Of the three, *Vanessa indica* showed the highest visitation rate, followed by *Aglais caschmirensis* and *Gonepteryx rhamni*, as represented in (Figure 4.41).

Environmental factors played a significant role in shaping pollinator behavior. Temperature and humidity were found to be key drivers of visitation frequency. An



Figure 4. 40 Pollinators of Uttarakhand

(A) *Pycnonotus leucogenys* (B) *Zosterops palpebrosus* (C) *Machlolophus xanthogenys* (D) *Parus cinereus* (E) *Dendrocopos macei* (F) *Passer domesticus*



Figure 4. 41 Pollinators of Uttarakhand

(G) *Turdoides striata* (H) *Parus cinereus* (I) *Pycnonotus cafer* (J) *Parus monticolus* (K) *Hypsipetes leucocephalus* (L) *Garrulus lanceolatus*



Figure 4. 42 Pollinators of Uttarakhand

(M) *Trochalopteron lineatum* (N) *Heterophasia capistrata* (O) *Passer cinnamomeus* (P) *Aglais caschmirensis* (Q) *Delias belladonna* (R) *Vanessa indica*



Figure 4. 43 Pollinators of Uttarakhand

(S) *Gonepteryx rhamni* (T) *Bombus haemorrhoidalis* (U) *Vespa basalis*

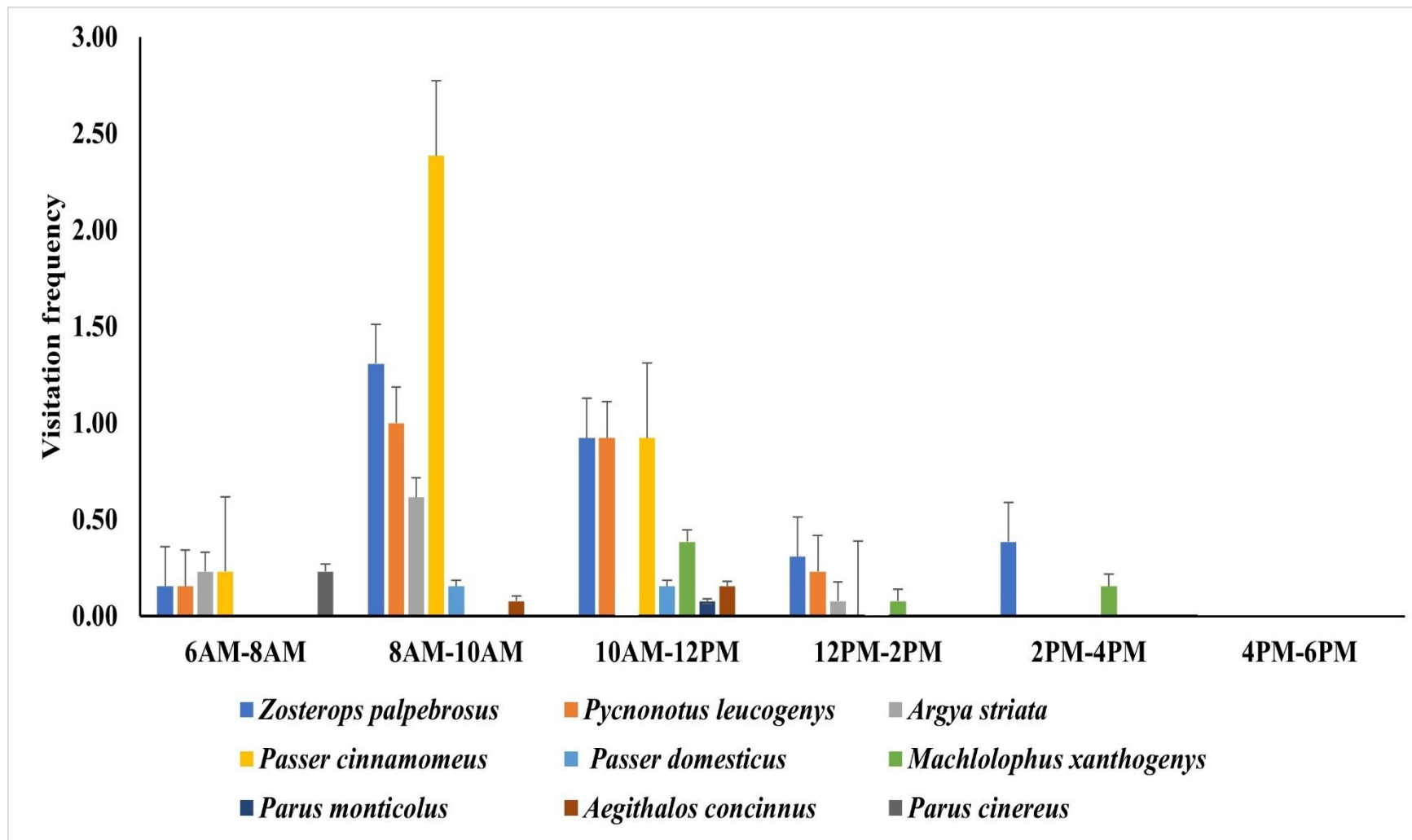


Figure 4. 44 Visitation frequency of birds in Uttarakhand, 2019 (N= 10 trees, Mean $\pm$ SE)

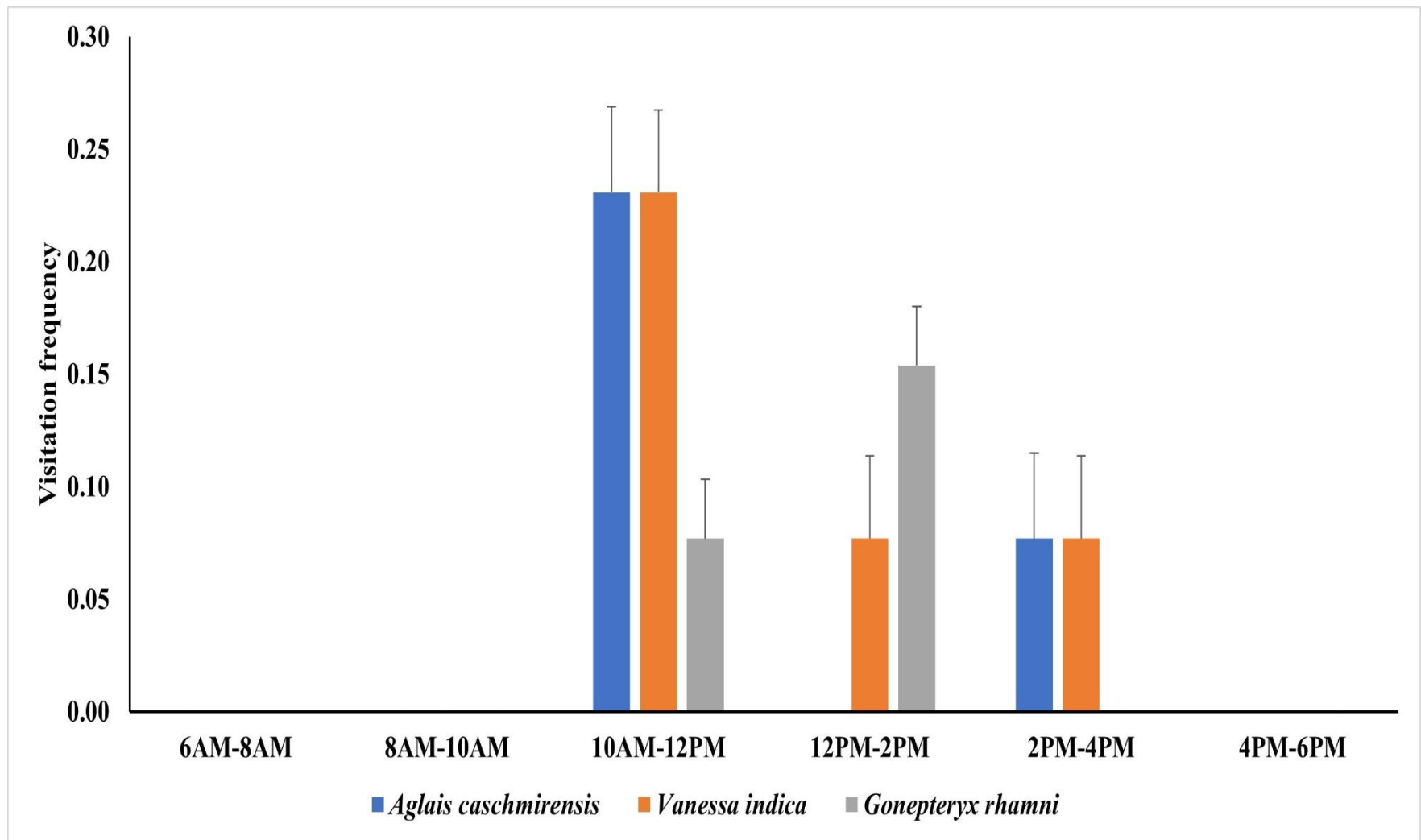


Figure 4. 45 Visitation frequency of butterflies in Uttarakhand, 2019 (N= 10 trees, Mean $\pm$ SE)

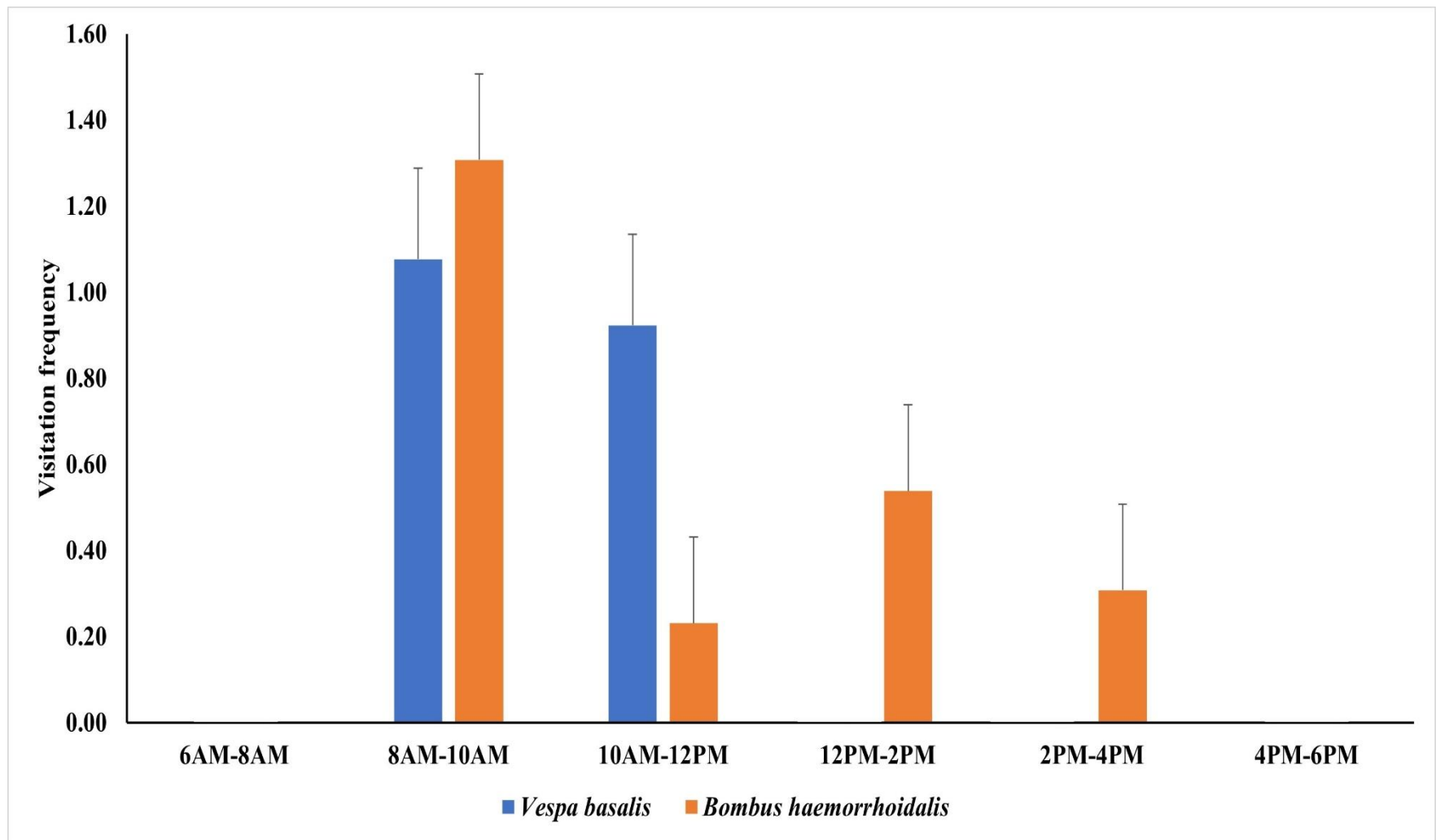


Figure 4. 46 Visitation Frequency of bees and hornets in Uttarakhand, 2019 (N= 10 trees, Mean $\pm$ SE)

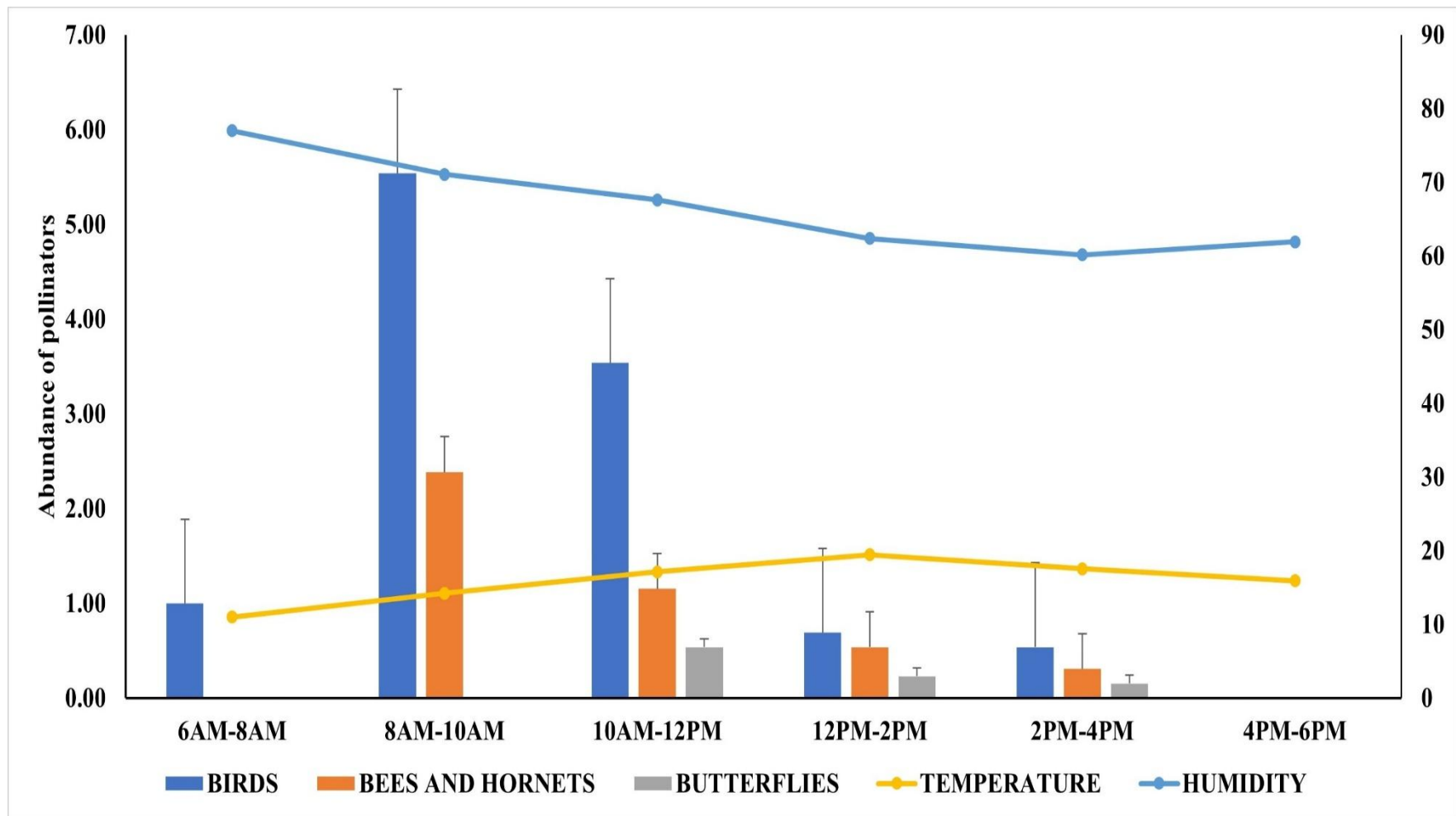


Figure 4. 47 Abundance of pollinators with respect to time, temperature and humidity, Uttarakhand, 2019 (N= 10 trees, Mean $\pm$ SE)

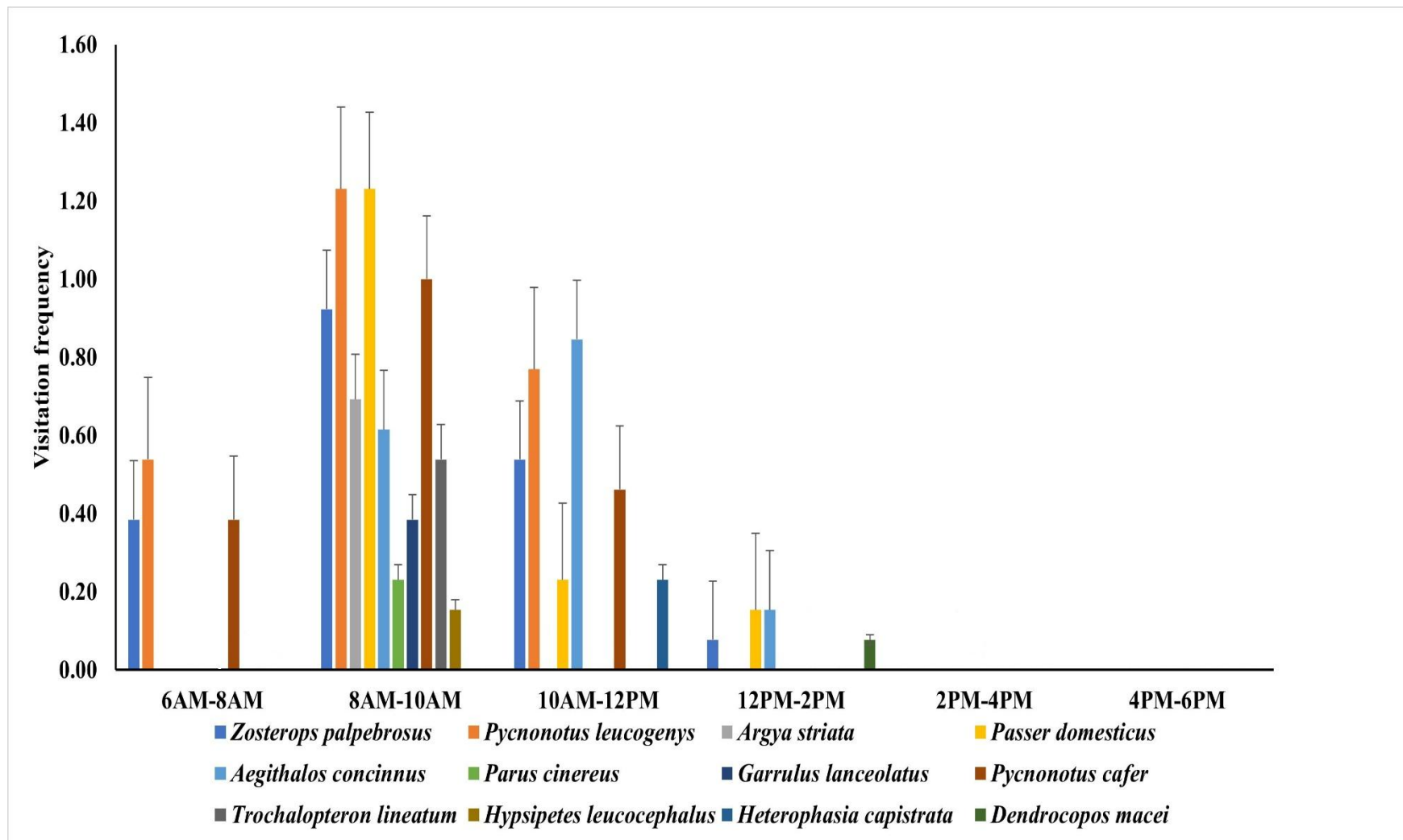


Figure 4. 48 Visitation frequency of birds in Uttarakhand, 2021 (N= 10 trees, Mean $\pm$ SE)

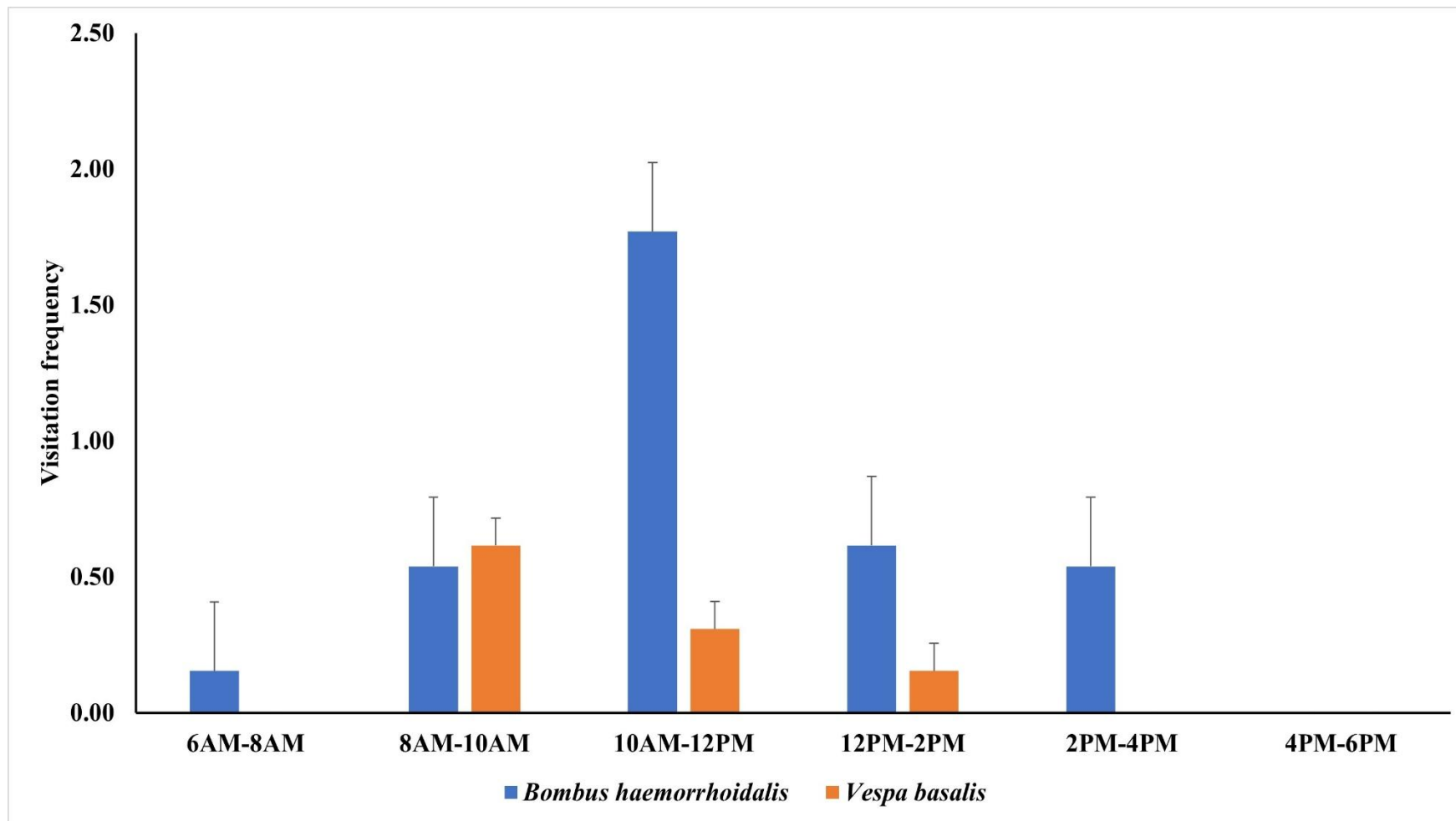


Figure 4. 49 Visitation frequency of bees and wasps in Uttarakhand, 2021 (N= 10 trees, Mean $\pm$ SE)

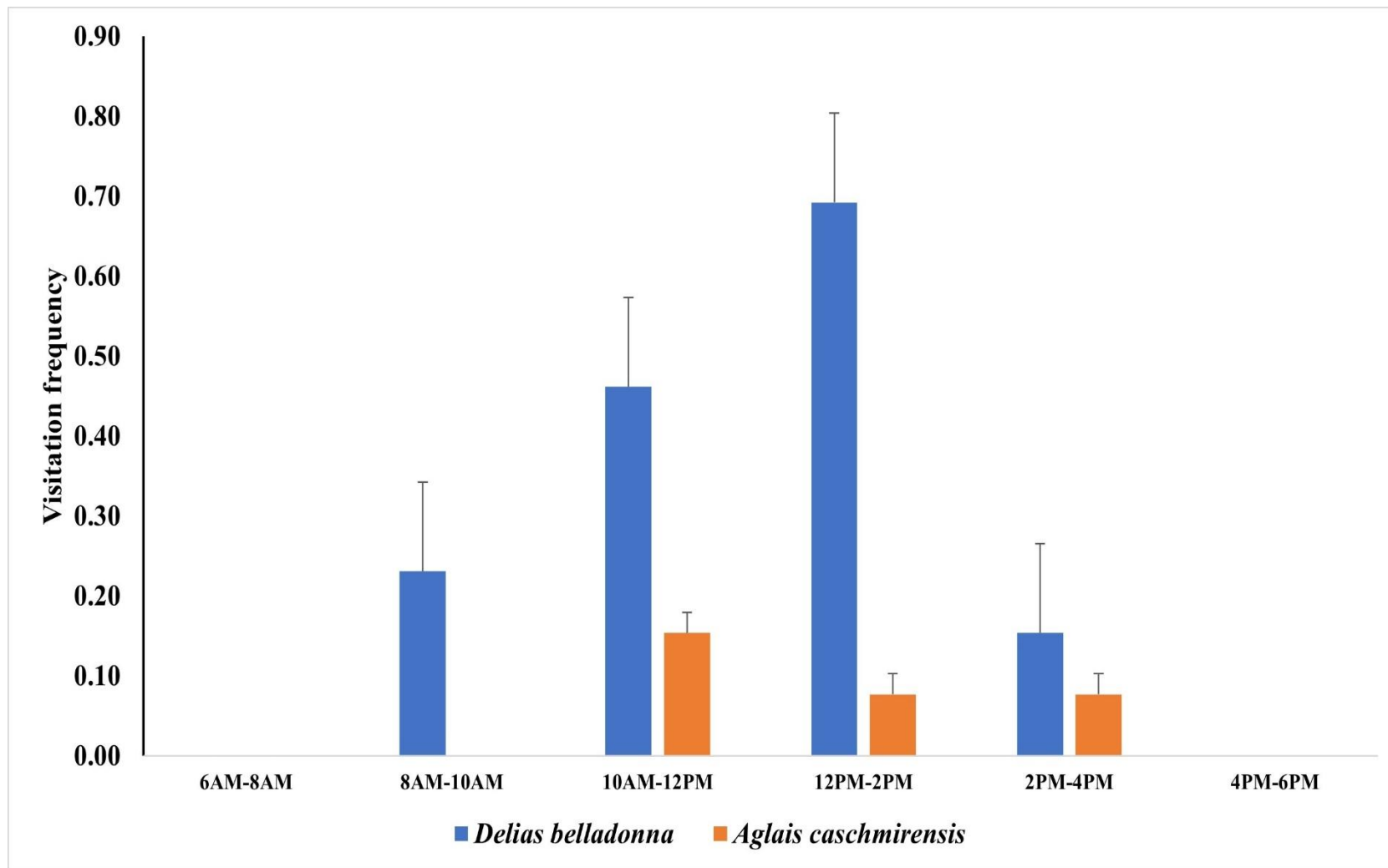


Figure 4. 50 Visitation frequency of butterflies in Uttarakhand, 2021 (N= 10 trees, Mean $\pm$ SE)

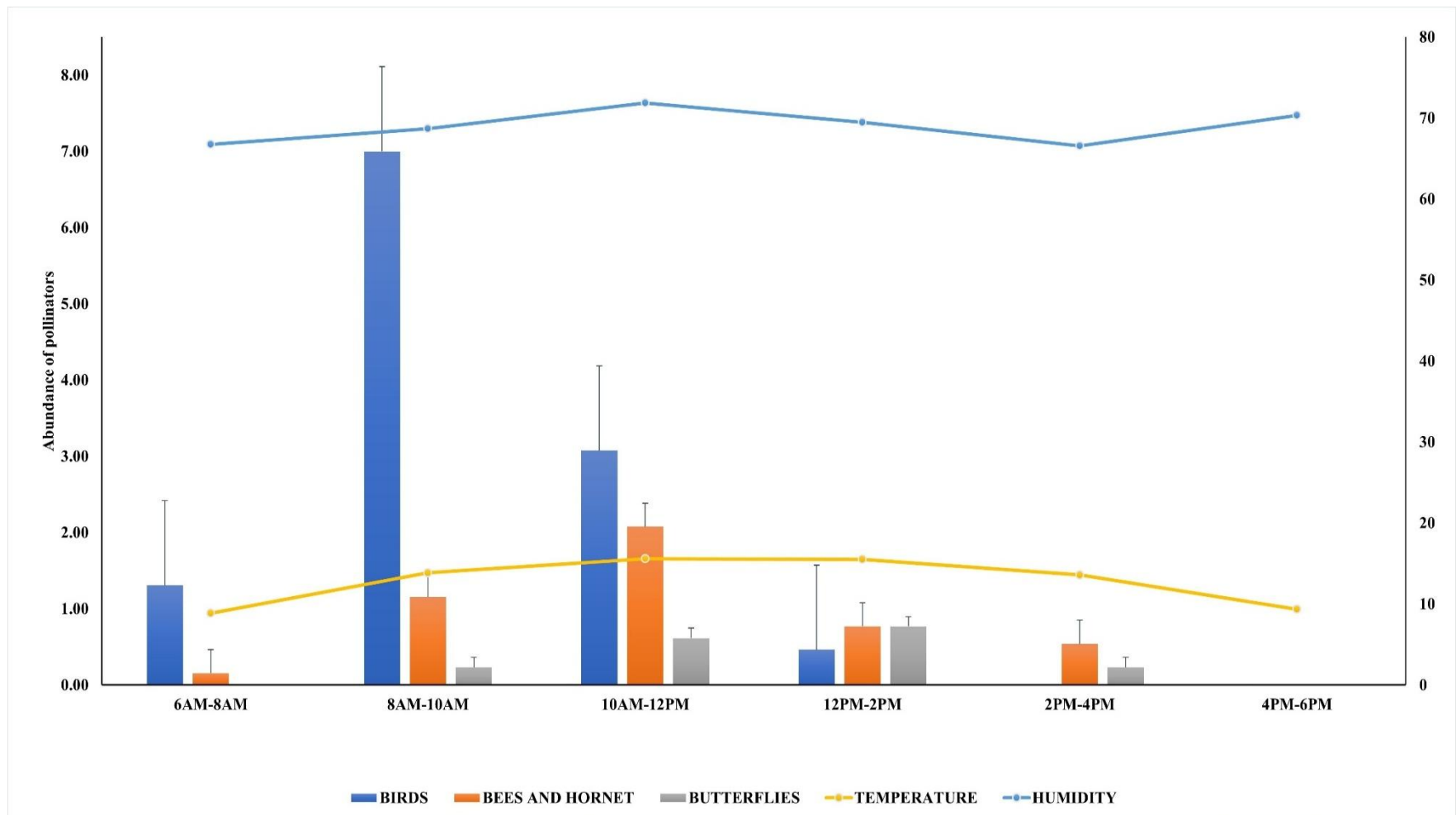


Figure 4. 51 Abundance of pollinators with respect to time, temperature and humidity, Uttarakhand, 2021(N= 10 trees, Mean $\pm$ SE)

increase in temperature correlated with heightened activity among pollinators such as birds, bees, and hornets. Conversely, declining temperatures were associated with a noticeable reduction in pollinator visits. This trend is depicted in (Figure 4. 42).

4.11 The pollinators availability in *P. cerasoides* for Uttarakhand (2021)

In 2021, a study conducted in Uttarakhand, India, focused on the pollination ecology of *P. cerasoides*. The results revealed that the species attracted a total of 12 avian visitors. These included *Zosterops palpebrosus* Temminck, *Pycnonotus leucogenys* Gray, *Argya striata* Dumont, *Passer domesticus* Linnaeus, *Aegithalos concinnus* Horsfield, *Parus cinereus* Vieillot, *Garrulus lanceolatus* Vigors, *Pycnonotus cafer* Linnaeus, *Trochaloxyron lineatum* Vigors, *Hypsipetes leucocephalus* Gmelin, *Heterophasia capistrata* Vigors, and *Dendrocopos macei* Vieillot. Additionally, two hymenopteran species, namely *Bombus haemorrhoidalis* Smith and *Vespa basalis* Smith, and two lepidopteran species, *Delias belladonna* Fabricius and *Aglaia caschmirensis* Kollar, were documented interacting with the flowers of *P. cerasoides* (Figure 4. 38).

Avian visitation was recorded continuously throughout the day. The highest levels of bird activity were documented between 8:00 a.m. and 10:00 a.m., while no avian pollinator activity was observed during the time intervals of 2:00 p.m. to 4:00 p.m. and 4:00 p.m. to 6:00 p.m. Among the bird species, *Pycnonotus leucogenys* demonstrated the highest visitation frequency to the flowers, as illustrated in (Figure 4.43).

Bombus haemorrhoidalis exhibited foraging activity throughout the diurnal period, with the exception of a marked absence during the 4:00 p.m. to 6:00 p.m. interval. Its peak visitation was recorded between 10:00 a.m. and 12:00 p.m. On the other hand, *Vespa basalis* showed maximum foraging activity during the 8:00 a.m. to 10:00 a.m. time slot (Figure 4.44).

Among the two recorded butterfly species, *Delias belladonna* showed a higher frequency of visitation than *Aglaia caschmirensis*, as depicted in (Figure 4.45). The patterns of pollinator visitation were found to be significantly influenced by ambient temperature and humidity. An increase in temperature was positively correlated with an increase in pollinator activity. Conversely, a drop in temperature was associated with a notable decline in both the presence and activity of pollinators.

Birds, in particular, exhibited peak visitation within the morning hours, primarily between 8:00 a.m. to 10:00 a.m. and 10:00 a.m. to 12:00 p.m., as demonstrated in (Figure 4.46). These findings underscore the importance of favorable environmental conditions in driving pollinator dynamics and floral visitation rates in *P. cerasoides*.

4.12 Correlation coefficient between pollinators, temperature and humidity in *P. cerasoides*, Mizoram 2019 and 2021

The correlation analysis of Mizoram in 2019 is presented in Table 4.26. The pollinators, specifically birds, exhibited a significant negative correlation with temperature ($r = -0.601, p = 0.087$). In contrast, bees, wasps, and hornets ($r = 0.105, p = 0.787$), butterflies ($r = 0.152, p = 0.697$), and squirrels ($r = 0.016, p = 0.967$) showed weak positive correlations with temperature. With respect to humidity, birds and squirrels showed negative correlations ($r = -0.248, p = 0.520$; $r = -0.282, p = 0.462$, respectively), whereas bees, wasps, and hornets ($r = 0.607, p = 0.083$) and butterflies ($r = 0.601, p = 0.087$) exhibited positive correlations, which approached significance. A statistically significant and strong positive correlation was observed between bees, wasps, and hornets and butterflies ($r = 0.816^{**}, p = 0.007$), indicating that their activity patterns were closely aligned.

The correlation analysis of Mizoram in 2021 is presented in Table 4.27. A significant positive correlation was observed between birds and bees/wasps/hornets ($r = 0.853^{**}, p = 0.003$). Butterflies also showed a significant positive correlation with humidity ($r = 0.685^*, p = 0.042$). Other correlations were not statistically significant, including birds and temperature ($r = 0.082, p = 0.833$), bees/wasps/hornets and temperature ($r =$

Table 4. 26 Correlation coefficient between pollinators, temperature and humidity in *P. cerasoides*, Mizoram 2019

		Birds	Bees, wasps & hornets	Butterflies	Squirrel	Temperature	Humidity
Birds	r	1					
	p						
Bees, wasps & hornets	r	-0.288	1				
	p	0.453					
Butterflies	r	-0.536	.816**	1			
	p	0.137	0.007				
Squirrel	r	0.462	-0.370	-0.370	1		
	p	0.210	0.326	0.328			
Temperature	r	-0.601	0.105	0.152	0.016	1	
	p	0.087	0.787	0.697	0.967		
Humidity	r	-0.248	0.607	0.601	-0.282	-0.377	1
	p	0.520	0.083	0.087	0.462	0.317	
**. Correlation is significant at the 0.01 level (2-tailed).							

Table 4. 27 Correlation coefficient between pollinators, temperature and humidity in *P. cerasoides*, Mizoram 2021

		Birds	Bees & hornets	Butterflies	Temperature	Humidity
Birds	r	1				
	p					
Bees & hornets	r	.853**	1			
	p	0.003				
Butterflies	r	0.291	0.160	1		
	p	0.448	0.681			
Temperature	r	0.082	0.366	0.063	1	
	p	0.833	0.333	0.873		
Humidity	r	0.499	0.180	.685*	-0.140	1
	p	0.172	0.643	0.042	0.720	
**. Correlation is significant at the 0.01 level (2-tailed).						
*. Correlation is significant at the 0.05 level (2-tailed).						

0.366, $p = 0.333$), and butterflies and temperature ($r = 0.063$, $p = 0.873$). The correlation between butterflies and bees/wasps/hornets was low ($r = 0.160$, $p = 0.681$), and the correlation between birds and temperature was moderate ($r = 0.499$, $p = 0.172$), but neither was statistically significant.

4.13 Correlation coefficient between pollinators, temperature and humidity in *P. cerasoides*, Uttarakhand 2019 and 2021

Table 4.28 shows the correlation analysis for Uttarakhand in 2019. Birds, bees and hornets, and butterflies showed weak positive correlations with temperature ($r = 0.186$, $p = 0.544$; $r = -0.214$, $p = 0.482$; and $r = -0.029$, $p = 0.924$, respectively), none of which were statistically significant. A significant negative correlation was observed between temperature and humidity ($r = -0.680^*$, $p = 0.011$). Birds showed a negative but non-significant correlation with humidity ($r = -0.354$, $p = 0.235$), while bees and hornets, as well as butterflies, showed weak positive correlations with humidity ($r = 0.238$, $p = 0.433$ and $r = 0.223$, $p = 0.464$, respectively).

Table 4.29 presents the correlation analysis for Uttarakhand in 2021. Bees and hornets showed negative correlations with temperature, with coefficients of $r = -0.277$ ($p = 0.360$) and $r = -0.072$ ($p = 0.816$), respectively. Birds, on the other hand, showed a weak positive correlation with temperature ($r = 0.167$, $p = 0.585$). Regarding humidity, birds and butterflies showed weak positive correlations with coefficients of $r = 0.252$ ($p = 0.405$) and $r = 0.064$ ($p = 0.836$), respectively. Bees and hornets had a negative correlation with humidity ($r = -0.157$, $p = 0.607$). None of these correlations were statistically significant.

4.14 Similarity coefficient of pollinators for Uttarakhand and Mizoram

Our study identified pollinator visitors across two distinct eco-regions: Mizoram and Uttarakhand. Among the recorded species, two pollinators *Pycnonotus cafer* and *Zosterops palpebrosus* were observed as common to both regions, visiting flowers at both study sites during the observation period. The similarity index between the two

sites was calculated to be 16.11%, indicating a low degree of overlap in pollinator communities.

The pollinator species recorded for each region included: in Mizoram, *Aethopyga gouldiae*, *Apis cerana*, *Appias olferna*, *Arachnothera longirostra*, *Callosciurus pygerythrus*, *Delias acalis*, *Delias descombesi*, *Delias hyparete*, *Delias pasithoe*, *Delta esuriens*, *Horornis brunnescens*, *Orthotomus sutorius*, *Pantoporia hordonia*, *Phylloscopus pulcher*, *Pycnonotus cafer*, *Vespa velutina*, *Vindula erota*, and *Zosterops palpebrosus*; and in Uttarakhand, *Aegithalos concinnus*, *Aglais caschmirensis*, *Argya striata*, *Bombus haemorrhoidalis*, *Delias belladonna*, *Dendrocopos macei*, *Garrulus lanceolatus*, *Gonepteryx rhamni*, *Heterophasia capistrata*, *Hypsipetes leucocephalus*, *Parus cinereus*, *Passer domesticus*, *Passer rutilans*, *Pycnonotus cafer*, *Pycnonotus leucogenys*, *Trochalopteron lineatum*, *Vanessa indica*, *Vespa basalis*, and *Zosterops palpebrosus*. (Table 4.30)

Table 4. 28 Correlation coefficient between pollinators, temperature and humidity in *P. cerasoides*, Uttarakhand 2019

		Birds	Bees & hornets	Butterflies	Temperature	Humidity
Birds	r	1				
	p					
Bees & hornets	r	0.183	1			
	p	0.549				
Butterflies	r	0.224	0.028	1		
	p	0.463	0.927			
Temperature	r	0.186	-0.214	-0.029	1	
	p	0.544	0.482	0.924		
Humidity	r	-0.354	0.238	0.223	-.680*	1
	p	0.235	0.433	0.464	0.011	
*. Correlation is significant at the 0.05 level (2-tailed).						

Table 4. 29 Correlation coefficient between pollinators, temperature and humidity in *P. cerasoides*, Uttarakhand 2021

		Birds	Bees & hornets	Butterflies	Temperature	Humidity
Birds	r	1				
	p					
Bees & hornets	r	-0.150	1			
	p	0.625				
Butterflies	r	0.072	-0.074	1		
	p	0.816	0.811			
Temperature	r	0.167	-0.277	-0.072	1	
	p	0.585	0.360	0.816		
Humidity	r	0.252	-0.157	0.064	.598*	1
	p	0.405	0.607	0.836	0.031	
*. Correlation is significant at the 0.05 level (2-tailed).						

Table 4. 30 Similarity coefficient for pollinators between Mizoram and Uttarakhand

	Mizoram	Uttarakhand
Mizoram	0	16.11
Uttarakhand	16.11	0

CHAPTER 5

Discussion

5.1 Reproductive phenology

The timings of seasonal or cyclical events biologically for flowering of plants plays a crucial role in its study and behavioural aspects. *P. cerasoides* is present in the temperate Himalayan region (eFloras, 2012) as well as in the tropical rainforest climate of the Cibodas Botanical Garden (Kurniawan *et al.*, 2021). As previously mentioned, distinct comparable habitats for my research species were discovered. In my study site in Uttarakhand, flowering patterns varied annually, occurred from late October to mid-November (2019-2023). In Mizoram, flowering was observed between November and December (2019-2023). This trend is consistent with findings from temperate deciduous broadleaf forests in China, where autumn phenology, such as end-of-season leaf senescence, occurs earlier at higher latitudes and elevations. This pattern is attributed primarily to geographic variations in temperature, rather than differences in precipitation (Lang *et al.*, 2019).

Hatta *et al.* (2005) have documented the flowering timing of *P. cerasoides* in CBG, indicating that it may undergo two flowering cycles annually. In addition, according to Normasiwi (2015), there was a biannual flowering period from 2009 to 2012, with a subsequent limited fruiting season occurring typically from July to September. Nevertheless, it has never reached a state of full maturity as a fruit. Furthermore, the data revealed that from 2001 to 2020, the occurrence of full fruit was only observed once in 2015, with a remarkably low frequency or intensity (Kurniawan *et al.*, 2021). Notably, my observations indicated that the species flowered only once a year, contrasting with the findings reported in previous studies (Normasiwi, 2015; Kurniawan *et al.*, 2021). The time of flowering and fruit drops are also closely related because when similar species grow together, their phenological responses are also common (Davies *et al.*, 2013). Also, the flowering of the plant

population lasted longer than the individual plants. This might be due to environmental factors owing to rainfall and temperature (Normasiwi,2015).

An earlier study suggested that the flowering and fruiting patterns of *P. cerasoides* might be more affected by biological factors than by relative humidity, temperature, and rainfall. This insight could provide valuable information for exploring and investigating other factors that influence the flowering process (Kurniawan *et al.*, 2021). There is high plant species diversity available with intriguing factors responsible for reproductive phenological diversity in tropical forests (Sakai and Kitajima, 2019). This can be due to the effect created by sunlight, humidity and pollinators (Li *et al.*, 2010). The pollinating insects are also affected by rainfall and temperature inhibiting the success of fruit formation Li *et al.*, (Darma, 2003). Although there were correlations with the rainfall, temperature and humidity between the two regions, the difference in fruit set percentage of *P. cerasoides* can be because of decreased visitation by pollinators (Roversi and Ughini ,1993). But the phenology for both tropical and temperate forest regions are different fundamentally (Abernethy *et al.*,2018). Although there are not much of a difference in its flowering patterns, it is also highly affected by the rainfall and temperature (Normasiwi, 2015).

Plant phenology is tightly linked and responsive to climatic factors and global warming (Sparks and Menzel, 2002). Temperature plays a pivotal role in the plant's phenological processes. The rise in temperature can either shorten or lengthen the flowering duration with respect to cold weather conditions (Lakatos *et al.*, 2009). Higher temperatures increase fruit set (Roversi and Ughini, 1993). Species of related families have similar factors in their phenological response (Davies *et al.*, 2013). Altitudinal or latitudinal patterns also affect phenology (Bertin,2008). Changes in plant phenology have important implications for ecosystem carbon cycles and ecosystem feedback to climate, yet the quantification of such impact remains challenging (Piao *et al.*, 2019). The statistical approaches correlate the timing of phenological events to environmental factors or heat unit accumulations, having simplified calculation procedures and correct phenological mechanism assumptions but limited applications and predictive abilities (Zhao *et al.*, 2013).

Shifting phenology has been discovered by researchers across various disciplines or multiple scales, including earlier spring flowering in individual plants and an earlier spring greening of the land surface (Cleland *et al.*, 2007). Based on the evaluation and observation of the flowering and fruiting phenology of *P. cerasoides* in these two regions, varied climatic factors and different groups of floral visitors could be probable reasons. The present study has discerned fundamental flowering patterns within the examined tree species. Notably, flowering has been observed during the leafless phase in *P. cerasoides*, as in case of tropical tree species investigation of *Firmiana colonrata* (Kumar, 2016). This aligns with evidence put forth by Janzen (1967) and Shukla and Ramakrishnan (1982), suggesting that the relative leaflessness of the canopy during flowering in *Firmiana colonrata* and *Gmelina arborea* may be a strategic adaptation. This strategy is thought to aid animal pollinators, such as insects and birds, in pollen transfer by enhancing visibility and accessibility to the flowers.

During the leafless period, numerous deciduous plants engage in flowering and fruit-bearing, utilizing terminal buds to facilitate this process (Janzen, 1976; Frankie *et al.*, 1974b). Observations in *P. cerasoides* revealed fluctuations in the timing of first flowering, the flowering peak, and the overall duration of flowering among individuals within a single year. This variability aligns with scientific findings reported by Khanduri (2012a) on *Tectona grandis* in Mizoram. The observed fluctuations in the timing of flowering were not confined to a specific region, as the study spanned both tropical and temperate forest. *P. cerasoides* displayed annual variations in flowering, with differing degrees of change noted. In the tropical forest, the species exhibited flowering during the months of November and December, while in the temperate forest, blooms occurred specifically in October and November during study period. This yearly variability underscores the adaptability of *P. cerasoides* to diverse environmental conditions, further emphasizing its ecological significance. Additionally, the findings highlight the potential role of tree species, that flower in the absence of leaves as a key and umbrella species, providing essential food supplies during periods of scarcity (Murali and Sukumar, 1994).

The synchronization of flowering within a population plays a pivotal role in shaping genetic exchange among conspecific plant individuals during a given reproductive season, as highlighted by Primack (1980). In populations exhibiting high synchrony, fewer plant individuals may have the greater opportunity to exchange genes. This phenomenon is particularly notable in insect-pollinated plant groups, where flowering synchrony enhances cross-pollination among individuals. The relative costs and benefits associated with population-level flowering synchrony are contingent upon the reproductive system of the plant species.

Brown and Kodric-Brown (1979) and Augspurger (1981) have emphasized potential benefits, including heightened pollinator attraction, while Rathcke and Lacey (1985) underscore increased out-crossing frequency. The significance of synchronization in flowering becomes evident in its impact on seed production and outcrossing levels. Achieving optimal seed production and maximizing outcrossing depend on the degree of synchronization within the population, ultimately influencing the distribution of genetic variation (Medan *et al.*, 2013). Augspurger (1983b) further stresses that the synchronization of flowering individuals enhances cross-pollination by attracting pollinators.

The frequency of pollinator visits and the reproductive success of plants are positively correlated with a high degree of synchronization in flowering (Gross and Werner, 1983). However, this increased synchronization comes with breeding implications, as highlighted by Primack (1980), leading to a decreased capacity for gene exchange among individuals within a plant species during a specific reproductive season. The winter blossoming of *P. cerasoides* serves as a food supply for pollinators during a time when resources such as nectar and pollen are scarce. Additionally, its stunning bloom adds aesthetic value and helps maintain ecological balance, while other species are dormant. Consequently, reduced competition among pollinators enhances the effectiveness of pollination, thereby, contributing to reproductive success.

5.2 Floral biology: anthesis, stigma receptivity and anther dehiscence of *P. cerasoides* (Mizoram And UK)

The timing of anthesis observed in this study shows clear alignment with previously reported diurnal flowering patterns in various species. In *Lagerstroemia speciosa*, peak anthesis was recorded between 0800 and 1200 hours (Khanduri, 2011), while in *Oryza sativa*, the flowers predominantly opened in the early morning hours (Wang *et al.*, 2022). Similarly, the present study found that anthesis occurred throughout the day, with distinct peaks between 0600 and 0800 hours in Mizoram and between 0800 and 1000 hours in Uttarakhand. These patterns suggest that flower opening in *P. cerasoides* is influenced by early morning microclimatic conditions, particularly temperature and humidity. The temperature-dependent nature of anthesis is further supported by findings in *Schima wallichii* (Khanduri *et al.*, 2013).

Interestingly, contrasting anthesis patterns have been reported in other *Prunus* species. Wadhwa and Sihag noted peak anthesis between 1200 and 1400 hours in *P. domestica*, and Kour (2018) observed similar midday flowering in *P. salicina*. These findings highlight the diversity in anthesis timing across the genus *Prunus*, likely shaped by species-specific floral traits and ecological adaptations. The early morning anthesis in *P. cerasoides* may thus reflect a locally optimized strategy, possibly linked to pollinator activity or favorable environmental windows in its native habitats.

The anthesis pattern in *Bombax ceiba* occurs in the early morning, specifically between 0400 and 1000am. Anther dehiscence in *Bombax ceiba* occurs through longitudinal slits. Anthesis is typically facilitated by a combination of high humidity and low temperature. The dehiscence of the anther is crucial for pollination as it allows mature pollen grains to be accessible to wind and insects, which then transport them to the receptive surfaces of the stigma. This process greatly influences the success of pollination for a species and has a significant impact on the genetic composition of populations (Khanduri, 2011).

The stigma in many tree crops, such as peach, apricot, sweet cherry, apple, and kiwi, is typically observed to become responsive during or shortly after anthesis (Sanzol and Herrero, 2001). However, the specific timing of when the stigma becomes receptive to pollen can differ greatly depending on the species or cultivar, typically necessitating a period of delayed maturity after pollination. Herrero (1983) found that pear stigmas were not initially responsive during anthesis, but the germination of pollen improved throughout a 4-day period after flowering. Similarly, research on apricot has shown that the stigmas are not fully mature during the balloon stage, but they become more receptive 2 to 4 days after the anthesis (Egea *et al.*, 1991). Stigma receptivity in *Prunus dulcis*, as reported by Yi *et al.* (2006) is optimal only after flowers have progressed beyond the fully open stage and display flattened petals.

The stigmas of *P. cerasoides* remain receptive for a longer period of time (Normasiwi *et al.*, 2023). The responsiveness of the female reproductive organ of the flower is affected by both temperature and humidity (Vargas *et al.*, 2017; Khanduri *et al.*, 2013). Therefore, altering the receptivity is crucial for enhancing fertilisation and fruit development. The receptivity of *Prunus* species initiated five days before flower opening or anthesis and maintained receptivity until the withering stage. The study delineated a progression from lower receptivity during D-5 to D-4, medium receptivity during D-3 to D-2, and highest receptivity during D-1 to D-0, corresponding to the anthesis stage (Normasiwi *et al.*, 2024). In the present study on *P. cerasoides*, it was observed that the stigmas were receptive throughout the flowering period and our study also confirmed the pre-anthesis receptivity of *P. cerasoides*. However, we found that the stigma exhibited optimal receptivity between 8 am to 10 am where the anthesis were just observed, which persisted consistently until the withering stage.

The anther dehiscence in *Erythrina stricta*, *Mesua ferrea*, *Schima wallichii*, occurs during the day through longitudinal slits. The dehiscence of the anther is greatly influenced by climatic variables (Khanduri, 2011). Anthesis and anther dehiscence are crucial factors for evaluating the following release and transport of pollen grains (male gamete) into the stigma of the pistil. When anthers dehisce or split open, they provide precise measurements of the amount of pollen released each day. Anther dehiscence is

a process that occurs in three different stages: (i) dehiscence of the anther begins before anthesis (ii) anther dehiscence coincides with anthesis (iii) anther dehiscence occurs after anthesis (Bhattacharya *et al.*, 1999). Observations of my research species indicate that it undergoes dehiscence after anthesis. When the humidity in the atmosphere is low and the temperature is high up to a certain point, it increases the occurrence of anther dehiscence (Khanduri and Sharma ,2000)

5.3 Mating system

The most efficient method of producing fruit in the *P. cerasoides* is cross-pollination, or allogamy, which yields 55.25% of the fruit. Following at 50.75% is open pollination, followed by geitonogamy at 48.00% and autogamy (self-pollination) at 42.50 (Normasiwi *et al.*, 2023). Open pollination, self-pollination, cross-pollination, and geitonogamy were studied in *Prunus* spp., revealing that cross-pollination resulted in a higher percentage of fruit (66.33%) compared to open pollination, self-pollination, or geitonogamy (Normasiwi *et al.*, 2024). In *I. triloba*, hand cross-pollination (xenogamous) consistently achieved over 70% fruit production across all cases. Open natural pollination also proved effective, yielding fruit settings exceeding 55%. Emasculated flowers covered with mosquito nets showed minimal occurrence of apomixis, underscoring the essential role of insect pollination.

Autonomous self-pollination and geitonogamous self-pollination exhibited lower fruit production percentages. Emasculation-open and natural pollination treatments demonstrated moderate fruit sets, Xenogamy and pollen supplementation treatments resulted in higher fruit settings compared to natural pollination (Paul *et al.*,2024). In *Schima wallichii* hand cross-pollination produced the highest amounts of fruit and seed settings, while open pollination produced slightly less fruit and seed than hand cross-pollination. The least amount of fruit and seed sets were seen in autogamous self-pollination (Khanduri *et al.*,2013). According to Baishnab *et al.* (2024), the fruit set percentages for naturally pollinated *Cymbidium aloifolium* ranged from $13.37 \pm 9.73\%$ to $16.42 \pm 3.34\%$ in 2018 and from 13.96% to 15.43% in 2019. In contrast, the emasculation open treatment in 2019 resulted in fruit set percentages of 15.91% at the

Sipahijala study site and 12.26% at the Suryamaninagar site, while bagged flowers at both locations produced no fruit set.

The present study revealed that *P. cerasoides* exhibits partial self-compatibility. Fruit set occurred under natural, open cross-pollination and hand-cross pollination treatments, while hand self-pollination and autogamy resulted in significantly lower success. No fruit set was observed in apomictic conditions, confirming that pollination is essential for reproduction in this species. These results align with patterns seen in other woody perennials. In *Eriobotrya japonica*, for instance, open pollination led to the highest fruit set, underscoring its reliance on insect-mediated cross-pollination (Chauhan, 2019). *Bauhinia forficata* also displayed strong self-incompatibility, with lower fruit set under selfing and limitations linked to habitat disturbance (Neto, 2013). Similarly, *Prunus salicina* cultivars showed variable compatibility; ‘Satluj Purple’ was strongly self-incompatible, whereas ‘Kala Amritsari’ exhibited partial self-compatibility with improved results under cross-pollination (Dongariyal *et al.*, 2022).

In *P. cerasoides*, the highest fruit set under natural and open pollination emphasizes the importance of biotic pollinators and compatible pollen sources. These findings not only affirm the species’ dependence on cross-pollination but also highlight the broader role of ecological interactions in maintaining reproductive success, with implications for its conservation and management in native habitats. These findings underscore the crucial role of pollinators in delivering pollen to the stigma of flowers, which facilitates the fertilization of the ovary and the production of fruit and seeds. The lower fruit set percentages observed after certain treatments suggest potential pollen limitation; reduced pollen supply and the exclusion of pollinators can lead to this limitation, ultimately resulting in decreased fruit set in plants. The success rate of pollination and fertilization can be affected by multiple factors. In addition to the compatibility between male and female gametes, environmental conditions also play a significant role in influencing pollination outcomes. Moreover, fertilization failure in plants can result from factors such as sterile pollen and ovules or incompatibility between the pollen and ovules (Kartikawati, 2008).

5.4 Pollen production

The findings on pollen production in *P. cerasoides* indicate that there is a variation in production capacity between the two sites i.e. tropical (Mizoram) and temperate (Uttarakhand). Additionally, the level of pollen production for each species is influenced by its genotype (Reddi and Reddi 1986). Pollen production, quantified by the number of grains per anther, varies significantly across different genera and species, even within the same genus (Reddi and Reddi, 1986). The number of pollen grains per anther, along with the number of anthers per flower, determines the overall pollen yield per tree, which in turn affects pollination success, as measured by fruit set following natural pollination. Pollen counts per anther can vary significantly under different environmental conditions (Khanduri *et al.*, 2015a).

The study revealed significant variability in the number of pollen grains per anther between the two locations. In Uttarakhand, the maximum recorded pollen grains per anther were 1363.86 ± 117.58 in 2019 and 1358.57 ± 90.53 in 2021, compared to Mizoram's values of 1219.20 ± 84.17 in 2019 and 1331.12 ± 60.42 in 2021. These findings reflect regional differences in pollen production, similar to studies conducted by Khanduri *et al.* (2015a) on tropical species, which reported that *B. ceiba* produced the highest pollen grain count per anther at $18,610 \pm 1,189.49$, followed by *M. ferrea* ($3,676 \pm 185.53$), *S. wallichii* ($1,796 \pm 46.50$), *E. stricta* ($1,142 \pm 36.26$), and *L. speciosa* (840 ± 19.02).

Additionally, Hidalgo (1999) provides further context regarding pollen production in *Cupressus* species, with *C. sempervirens* producing $365,722 \pm 40,058$ grains, *C. macrocarpa* $383,600 \pm 16,350$ grains, and *C. arizonica* $333,433 \pm 29,581$ grains. This complementary data underscores the substantial variability in pollen grain production across different species and environmental conditions, highlighting the importance of considering species-specific and site-specific factors when assessing pollen emissions and their ecological impacts.

Additionally, significant variations in pollen grain counts per anther have been documented in *B.ceiba*, such as the estimation of 88,630 pollen grains per anther in Santiniketan, Kolkata (Bhattacharya and Mandal, 2000), and $6,308 \pm 14$ pollen grains per anther in Lambasingi–Lotugedda, located in the Eastern Ghats forests of Visakhapatnam District, Andhra Pradesh, India (Raju *et al.*, 2005). Variation in pollen production among various plant species, including closely related ones within the same family, is shaped by factors influencing male reproductive success (Garcia *et al.*, 2020). Essential data on pollen productivity play a vital role in the selection of male mates in plants (Vankin *et al.*, 2003). Numerous studies indicate that pollen production is a genetically determined trait, exhibiting significant variability not only between species but also among different cultivars (Anton and Denisow, 2018).

This trait is characterized by considerable variability among individuals of the same species and across different growing seasons, reflecting its non-fixed nature. External factors critically influence this variability (Alonso *et al.*, 2013). For instance, Hidalgo *et al.* (1999) found that flower density per plant affects pollen production and that the distribution of flowers within the crown is shaped by both environmental and genetic conditions.

Furthermore, high-quality and abundant pollen production is crucial for mating success, as flowers that produce larger quantities of pollen tend to attract more pollinators, thus promoting effective reproduction (Khanduri *et al.*, 2015a). Changes in microclimate can significantly impact the development of fruiting branches, inflorescences, flowers, and pollen grain production in *Olea europaea*, as noted by Aguilera and Valenzuela (2012). Khanduri (2012) highlighted that the timing of flowering and the amount of pollen and fruit produced by *Tectona grandis* exhibit seasonal variation. Similarly, annual fluctuations in reproductive phases, flower production, and pollen output have been reported for *Lagerstroemia speciosa* (Khanduri, 2014). *Schima wallichii* also shows significant yearly variability in the production of flowers, pollen, fruits, and seeds (Khanduri *et al.*, 2013).

Pollen production is a critical factor influencing the reproductive success of plants (Khanduri *et al.*, 2015a). Insufficient pollen production can negatively impact fruit and seed set among conspecific individuals within a population. For example, a study on *Taxus canadensis* found a correlation between seed set and both pollen and ovule production (Allison, 1990). Understanding the relationship between pollen availability and subsequent fruit and seed production is vital for facilitating gene flow among populations of both wind- and animal-pollinated species (Allison, 1990; Khanduri *et al.*, 2015b). In the present study, the estimated annual pollen production per tree for *P. cerasoides* in Mizoram was 1.9×10^9 in 2019 and 2.3×10^9 in 2021, while in Uttarakhand, the total pollen output per tree was recorded as 2.6×10^9 in 2019 and 2.4×10^9 in 2021.

When compared to other species, the pollen production levels for *P. cerasoides* fall within the expected range for a variety of tree species. For instance, the pollen production per tree for species like *Acer negundo* ranges from 15.2×10^9 to 250.1×10^9 (Molina *et al.*, 1996), and for *Fraxinus angustifolia*, it ranges from 11.2×10^9 to 160.7×10^9 . Other species such as *Lannea coromandelica* produce pollen in the range of 1.8×10^9 to 2.8×10^9 (Molina *et al.*, 1996), which is comparable to the values observed in *P. cerasoides* in Mizoram and Uttarakhand. Additionally, pollen production in species like *Grevillea robusta* (0.104×10^9 to 0.116×10^9 , Khanduri and Sharma, 2002b) and *Lagerstroemia speciosa* (5.12×10^7 to 91.87×10^7 , Khanduri *et al.*, 2015a). The comparison with *L. speciosa* (Khanduri *et al.*, 2015a), which showed a pollen production range of 5.12×10^7 to 91.87×10^7 , further emphasizes the variability in pollen production among different species.

This wide range of pollen production values across different tree species supports the notion that *P. cerasoides* exhibits pollen production within the expected range for tree species in similar environmental conditions. The comparison with the data on *L. speciosa* (Khanduri *et al.*, 2015a), which showed a pollen production range of 5.12×10^7 to 91.87×10^7 , also emphasizes the broader patterns of pollen production within the same ecological or taxonomic group. In the present study, significant effects of population were observed on various reproductive traits, including pollen per tree (F

= 12.62, $p = 0.00104$), pollen per anther ($F = 7.28$, $p = 0.0106$), and fruit set per tree ($F = 296.40$, $p < 0.00001$). These findings align with similar studies, such as those by Khanduri *et al.* (2015a) on *L. speciosa*, which also reported significant population effects on pollen production per tree ($F = 24.17$, $P = 0.0003$) and fruit setting per tree ($F = 26.54$, $P = 0.0002$). While both studies highlight the influence of population on reproductive traits, the specific F-values and p-values differ, likely due to differences in species, experimental design, and environmental factors. The number of flowers per tree for *C. sempervirens* is 176,223, for *C. arizonica* is 368,743, and for *C. macrocarpa* is 2,974,651. In comparison, my study found the following flower counts: in Mizoram, there were 44,181.61 flowers per tree in 2019 and 49,383.48 in 2021, while in Uttarakhand, there were 47,271.68 flowers per tree in 2019 and 45,360.82 in 2021.

5.5 Pollinators availability

P. cerasoides depends heavily on bees, butterflies, and other insects in its natural habitat for the transfer of pollen between the male and female floral organs. This process is essential for fertilization and seed production. Although the species is partially self-compatible, meaning it can fertilize its own flowers to some extent, it primarily promotes cross-pollination between different individuals to enhance genetic diversity within populations. Following fertilization, the flowers mature into small cherry-like fruits, which encase the seeds. These fruits are primarily dispersed by birds and mammals that consume them, contributing to seed dispersal and recruitment.

In our study we observed that in Mizoram, seven passeriformes birds ,classified into seven families; and one hoary-bellied Himalayan squirrel (also known as an Irrawaddy squirrel) is classified into the Scuridae family, and similar pollinators were also observed on Liana by Kumar *et al.*, 2022. In Uttarakhand, eleven passeriformes and one piciformes birds are classified into nine families, similar pollinators were also observed on Liana by Kumar *et al.*, 2022 .These pollinators were discovered visiting the *P. cerasoides* blossoms during its blooming stage. Passerine birds have accurate and consistent contact with floral components, particularly the stigma and stamens, using their bills, head, and breast. As a result of this interaction, these birds' heads and

crowns get dusted with pollen grains (Khanduri *et al.*, 2021). Pollen grains stick to the heads or breasts of nectivorous birds after they eat nectar, which helps spread pollen from blossom to flower. Studies by Mitchell *et al.*, (2009) and Cruden and Toledo, (1977) have documented this occurrence. It is worth noting that *P. cerasoides* produces flowers in the winter, providing a significant nectar and pollen supply for bees, wasps, hornets, and birds. In Mizoram, *P. cerasoides* was frequented by seven distinct avian species and witnessed interactions with three Hymenoptera insect species and seven Lepidoptera species. Contrastingly, in Uttarakhand, this plant species attracted visits from 13 notable bird species, along with two Hymenoptera insects and four Lepidoptera species.

P. cerasoides were visited by members of bird's species which remain consistent and also to be one of the important pollinators according to its visitation frequency. In Mizoram, the types of birds that were commonly seen changed between 2019 and 2021. In 2019, the primary floral visitor of *P. cerasoides* was *Pycnonotus cafer*, whereas in 2021, *Zosterops palpebrosus* was more frequently observed. A similar pattern was reported by Khanduri *et al.* (2021), where pollinators were found to regularly visit the flowers of *Erythrina stricta*. The significance of floral visits as possible pollinators has been defined by the behavioural traits of birds and the properties of flowers (Kevan, 1999). These changes could be influenced by factors like food availability, climate conditions, and changes in their habitats. The fact that birds consistently visited between 10 a.m. and 12 p.m. suggests that they have a preference for those hours when the weather is likely to be optimal. In Uttarakhand, a variety of bird species were observed in both 2019 and 2021. In 2019, the notable species were *Pycnonotus leucogenys* and *Pycnonotus cafer*, while in 2021, there were bird species visiting.

The highest level of activity occurred between 8 a.m. and 10 a.m., indicating that avian pollinators generally prefer morning hours for their activities, in contrast to the timing of pollinators availability by the studies conducted by Khanduri *et al.*, 2021. In Mizoram, bees (*Apis cerana*) were consistently seen visiting flowers during the day in both 2019 and 2021, thus making it an additional significant pollinator, similar results

were reported by Kumar and Khanduri, 2016. Multiple avian species were recorded engaging in simultaneous feeding behaviour on the flowers of the same tree. Figures 4.28 A-F, figure 4.39 G (Mizoram), figure 4.40 A-F, figure 4.41 G-L, figure 4.42 M-O (Uttarakhand), present comprehensive visual records of the notable avian visitors, showcasing their intricate interactions with the reproductive structures of the flowers, including their beaks and other anatomical features (Khanduri *et al.*, 2021). Figure 4.29 H-L, figure 4.30 M-N (Mizoram) and figure 4.42 P-R (Uttarakhand) depict several species of butterflies, while figure 4.30 O-Q (Mizoram), figure 4.43 T-U (Uttarakhand) illustrate different types of bees, wasps, and hornets, respectively. The pollinator squirrel is depicted in figure 4.30 R. However, hornets (*Vespa velutina*) and wasps (*Delta esuriens*) had patterns displaying activity during specific times of the day. It is possible that their lack of visits is related to their resting periods.

Ueno (2015), investigated on hornets and reported that it possesses the potential to play a role in pollination, particularly under certain contextual conditions. In my study, it was observed that the bees, wasps and hornets were seen visiting the flowers to either harvest the nectar or pollen from the flowers, suggesting their involvement in the process of pollination. When they frequent their visits from flower to flower, they carry pollen which indicates their potential role as pollinator despite the fact that some people are scared of those insects because they may sting or attack, but in my study site, it was observed that they just flew without attacking when disturbed. In Uttarakhand, we observed two species. The bumblebee (*Bombus haemorrhoidalis*) and the hornet (*Vespa basalis*) showed preferences for hours. Bees exhibit a tendency to visit many flowers within the same inflorescence or across different inflorescences on a single plant before transitioning to neighbouring plants. Additionally, they may revisit the same flowers at a later time (Sun *et al.*, 1998). This highlights how temperature and daylight play a role in influencing their behavior.

According to Clarke *et al.*, (2013), bumble bees are able to recognize and distinguish flowers that other bees have previously visited by detecting the electric field. Additionally, Harrap *et al.*, (2017) found that bumbling bees can recognize flowers based on their temperature. Butterflies also played a role in pollination, with *Delias*

descombesi, being the most frequent visitor in Mizoram similar reports were stated by Ghazoul, 2004. Their preference for visiting flowers between 10:00 a.m. and 12:00 p.m. aligns with the patterns observed in bird pollinators. In Uttarakhand, we found *Delias belladonna* and *Aglaia caschmirensis*, which further demonstrate the diversity of butterfly pollinators with a preference for morning hours. The study revealed a disparity in butterfly populations between Uttarakhand and Mizoram, with Uttarakhand exhibiting a lower abundance. Conversely, the diversity of bird pollinators was found to be greater in Uttarakhand as compared to Mizoram. The avian pollinators exhibited a higher degree of sensitivity to auditory disturbances and physical disturbances in comparison to butterflies, bees, wasps, and hornets across both research locations. Bird pollinators had a higher frequency of visitation compared to other visitors at both research sites.

It is noteworthy that in Uttarakhand, there was a notable abundance of bird pollinators, displaying high levels of activity. Additionally, certain avian pollinators exhibited distinct characteristics that were not detected inside the region of Mizoram. However, there was limited documentation of spider hunting activities in Uttarakhand. The diminutive arachnid predator, equipped with its minuscule elongated bill, procures the nectar. During this procedure, the insect comes into contact with the exposed anthers, facilitating the transfer of pollen onto the stigmas as it continues to visit various floral components. It is noteworthy to observe that a majority of avian pollinators emit a distinct vocalization or call before engaging in the collection of nectar or pollen. Kumar *et al.*, (2022) also documented similar findings on the Little Spider Hunter species. In a study conducted by Liu *et al.*, (2018) on *Cerasus cerasoides*, similar findings were reported, indicating a greater dependence on avian pollinators. This was observed despite the presence of both bird and insect visits on the plant.

Roversi and Ughini (1993) have shown a negative correlation between pollinator activity and environmental conditions which is observed in our studies. The research reveals temporal fluctuations in avian species preferences. Mizoram possibly supports adaptability of bird species to environmental changes. The temporal and resource characteristics of a region could serve as a determinant to different species to explore

unique ecological niches. These factors make the interactions between plants and pollinators an ongoing process. This study compares the relation between *P. cerasoides* and their different but highly specific pollinators as it relates to factors such as temperature, time of day and so on. Since changes in climate continue, understanding the complexities of these processes is crucial for protection and care of these ecosystems. Changing bird preferences through time demands that monitoring is continuous, and changes are made accordingly for conservation practices.

5.6 Pollen viability and the effects of growth hormones on *in vitro* pollen germination

In the current study, a 0.5% solution of TTC (2,3,5-triphenyltetrazolium chloride) was utilized to evaluate the vitality of pollen grains. The assessment was carried out on two discrete developmental phases of flowers, specifically pre-anthesis (flowers that have not yet opened) and anthesis (flowers that have opened). The examination of viability percentages revealed a significant difference between the pre-anthesis and anthesis stages. In a comparative analysis, it was shown that Mizoram continuously demonstrated lower viability percentages as compared to Uttarakhand. The gap seen can be ascribed to differences in climatic conditions and the ability of plant species to adjust to their specific habitats. It is worth noting that the anthesis stage resulted in more beneficial outcomes in relation to pollen viability.

Singh *et al.*, (2022) observed comparable findings in their study on *C. colebrookianum* and *C. infortunatum*, which is noteworthy to remark. A noticeable disparity in color was noted between viable pollen, which had a red stain, and non-viable pollen, which did not manifest any staining. Abdelgadir *et al.* (2012), Yaman and Turan (2021), Rico and Reyes (2019), and Buchner *et al.* (2022) have conducted multiple studies to examine the color discrepancy between viable and non-viable pollen in *Jatropha curcas*, *Prunus armeniaca*, *Bursera hybrids*, and *Fraxinus excelsior*, respectively, employing the TTC method. Yang *et al.* (2021) conducted a study to evaluate the reliability of the TTC test in the assessment of pollen viability for *Amomum villosum* and *Amomum longiligulare*. The findings of a notable proportion of post-anthesis

viability in both the study sites (Figure 4.24) are consistent with the findings reported for *Jatropha curcas* (Abdelgadir *et al.*, 2012), as well as *Passiflora cincinnata*, *Passiflora edulis*, *Passiflora edmundoi*, *Passiflora galbana*, *Passiflora gibertii*, and *Passiflora suberosa* (Soares *et al.*, 2013). The control condition in both the study sites resulted in a notably low percentage of *in vitro* pollen germination in Uttarakhand and Mizoram. This suggests that both species are susceptible to pollination and fertilization failure if they do not have access to suitable pollinators and receptive stigmas shortly after the release of pollen from the anthers (Sanjay *et al.*, 2016).

In vitro pollen germination was observed to be significantly enhanced with the introduction of sucrose at concentrations of 5% and 10% in comparison to the control group (distilled water) which highlights the crucial role of sucrose in providing essential nutrients for the development of pollen tubes. The aforementioned observation aligns with the findings of Sanjay *et al.* (2016) in their scholarly research on three tropical species. It is worth mentioning that Mizoram displayed lower germination percentages compared to Uttarakhand, which may indicate the existence of regional inequalities in pollen reactivity. The findings of the research done in Uttarakhand demonstrate the significant influence of concentration on pollen germination, specifically highlighting the huge impact of sucrose concentration in the medium. However, it was observed that Mizoram did not exhibit any variations that are statistically significant. This implies that there are factors at play beyond concentration and duration which impact the dynamics of pollen in this particular region.

Distinct patterns were seen in the evaluation of the influence of hormones on pollen germination. The results obtained in Mizoram indicate that a concentration of 100 mg L⁻¹ of GA₃ resulted in the maximum germination rate. This finding highlights the efficacy of GA₃ as a growth hormone. Gibberellins, or GA₃, are essential endogenous plant growth hormones that are involved in many aspects of plant growth and development, including anther development, floral induction, fruit and seed development, stem and leaf elongation, and seed germination (Sanjay *et al.*, 2016). Gibberellic acids (GA₃) have been found in pollen grains that are still developing after

anthesis. This shows that they play a role in many reproductive processes (Singh *et al.*, 2002). Sotomayor *et al.* (2012) reported that the application of GA₃ resulted in the most pronounced levels of pollen germination and pollen tube expansion in *Prunus dulcis*.

The study conducted by Ye *et al.* (2010) revealed that gibberellins had a substantial influence on pollen viability and pollen tube enlargement. Additionally, previous studies have demonstrated the efficacy of GA₃ in enhancing plant growth (Emam and Moaied, 2000) and increasing the root output of *Angelica dahurica* (Hou *et al.*, 2013). In vitro pollen germination in *Spathodea campanulata* was shown to be higher when compared to *Bauhania. variegata* and *Bauhania. purpurea* when exposed to Gibberellic Acid (GA₃). Gibberellins (GA₃) stimulate the process of germination by enhancing the activity of alpha amylase. Gibberellic acids (GA₃) are of significant importance in several plant growth and developmental processes, with specific emphasis on flower induction, elongation of leaves and stems, as well as the formation of fruits and seeds (Sun, 2004). According to Acar *et al.* (2010), there are reports suggesting that it can stimulate the formation of pollen tubes in *Pistacia vera* under *in vitro* conditions.

According to Singh *et al.* (2002) and Chhun *et al.* (2007), GA₃ affects pollen viability and pollen tube growth in Arabidopsis and rice. Nevertheless, it was shown that in Uttarakhand, the hormone GA₃ at a concentration of 100 mg L⁻¹ exhibited superior performance compared to other hormones. This finding is consistent with the acknowledged function of GA₃ in facilitating the formation of pollen tubes. Kinetin, particularly when administered at a concentration of 100 mg L⁻¹, exhibited significant outcomes. The application of kinetin consistently elicits a favourable effect on both pollen germination and pollen tube elongation. In a study conducted by Konar (1958), it was shown that kinetin exhibited the capacity to enhance both pollen germination and the elongation of the pollen tube in *Pinus roxburghii*. In a study conducted by Maita and Sotomayor (2015), it was observed that Kinetin had an impact on both pollen germination and tube growth in *Prunus dulcis*. It has been observed that applying kinetin at low concentrations increases *Prunus armeniaca* pollen germination

and pollen tube lengths; conversely, applying kinetin at high concentrations decreases pollen tube enlargement (Bolat and Pirlak, 1999). The consistent findings across several plant species provide additional support for the advantageous effects of kinetin in augmenting crucial elements of reproductive mechanisms. Four types of Hibiscus (Li *et al.*, 2015), including *Bauhinia purpurea* and *Bauhinia racemosa* (Sanjay *et al.*, 2016), as well as *Litchi chinensis* (Zeng *et al.*, 2018) and *Actinidia deliciosa* (Marques, 2018), had better chances of germinating *in vitro* pollen by IBA.

Indole-3-Acetic Acid (IAA) is a phytohormone that plays a crucial role in the phenomenon of sexual reproduction in plants. The hormone known as indole-3-acetic acid (IAA) is significantly involved in regulating the formation of reproductive structures such as the gynoecia, ovary, stamens, and egg cells (Nemhauser *et al.*, 2000). The research done by Abdelgadir *et al.* (2012) showed that the right amount of indole-3-acetic acid (IAA) is needed for pollen to germinate and tubes to form. Furthermore, Kovaleva *et al.* (2005) observed that lower quantities of IAA were found to facilitate pollen germination, but larger concentrations were shown to impede it. The quantity of indole-3-acetic acid (IAA) in the pistil increases during pollination, increasing the likelihood that the pollen tube will lengthen (Aloni *et al.*, 2006).

Research has indicated that indole-3-acetic acid (IAA) can lengthen pollen tubes and alter the structure and composition of the tube wall in vitro culture methods, particularly those used with plants such as *Torenia fournieri* (Wu *et al.*, 2008). In both study sites, the analysis demonstrated a reduced effectiveness for the hormones IBA and IAA. However, the lowest level of observation was found in IAA, which differs from the findings reported by Sanjay *et al.* (2016) in their study on *Bauhinia variegata* and *Bauhinia purpurea*. The *in vitro* pollen germination at both study sites was influenced and regulated by the hormones GA₃, Kinetin, IBA, and IAA. Nevertheless, the observed outcomes exhibited variability in response when subjected to various growth hormones and their respective treatments. All four growth hormones had an impact on pollen germination, but at different rates.

This observation suggests that the pollen grain of *P. cerasoides* displays discernible responses to several types of growth hormones. The difference in result observed between the two study sites may be due to its environment factor or the plant's adaptability to its location. This study makes substantial contributions to the comprehension of the diverse factors that influence pollen viability and germination in two geographic areas. The findings highlight the need to utilise geographically tailored approaches in reproductive biology research, considering the intricate interplay between environmental factors and plant physiological processes.

CHAPTER 6

Summary and Conclusion

6.1 Summary

The present study explores the reproductive ecology of *P. cerasoides*, a winter-blooming Himalayan cherry species, across tropical and temperate forest conditions in India. This research was conducted with the objective of understanding how reproductive processes such as phenology, pollen production, mating system, and pollinator availability contribute to the species' reproductive success under varying environmental conditions. Fieldwork was carried out between 2019-2023 in two geographically and climatically distinct sites: Mizoram (tropical) and Uttarakhand (temperate), offering a comparative framework for analysing ecological responses across regions.

Reproductive phenology, including flowering and fruiting patterns, was examined in natural populations at both sites. Observations revealed that *P. cerasoides* exhibited a seasonal flowering regime concentrated during the winter months. The onset, peak, and termination of flowering varied slightly between the two regions, with anthesis primarily occurring during the early morning hours. The synchronization of flowering within populations was found to be closely aligned with local temperature and humidity levels, which appeared to influence both the timing and intensity of floral display. The species displayed a relatively short flowering window, floral longevity, prolonged stigma receptivity was sufficient to support pollination across multiple days, even under fluctuating climatic conditions.

Pollen production was quantified at both the flower and tree levels. The analysis indicated that *P. cerasoides* produces a considerable amount of pollen, signifying a high reproductive potential. Detailed pollen studies included *in vitro* germination experiments, which confirmed the viability and functionality of pollen grains collected across both sites and years. The consistently observed germination patterns suggest

that pollen viability is not a limiting factor in the species' reproductive process. These findings highlight the physiological preparedness of *P.cerasoides* to achieve successful fertilization, provided adequate pollen transfer is facilitated through biotic agents.

To determine the breeding system and mating strategy of the species, a series of controlled pollination treatments were conducted. These included natural pollination, open cross-pollination, hand self-pollination, hand cross-pollination, geitonogamy, and apomixis. Results indicated that *P. cerasoides* is partially self-compatible. Natural and cross-pollination treatments consistently resulted in higher fruit set, while self-pollination and geitonogamy yielded comparatively lower success. No fruit development was observed under apomictic conditions, confirming that fertilization requires active pollen transfer and that the species is obligately sexual in reproduction.

Pollinator observations revealed a diverse assemblage of floral visitors, including birds, bees, butterflies, wasps, hornets, and a squirrel. These pollinators were recorded throughout the flowering period, with activity concentrated during specific hours of the day, largely aligned with anthesis. Notably, birds, particularly from the order Passeriformes, were identified as consistent and effective pollinators in both regions, though their species composition varied from year to year. In Mizoram, bird pollinator diversity fluctuated between years, while in Uttarakhand, a greater richness of avian species was consistently observed. Insects, particularly bees and butterflies, also contributed to pollination. Species such as *Apis cerana* and several lepidopterans were recorded with regular visitation patterns. Hornets and wasps, though less frequent, demonstrated behaviors suggestive of potential pollination roles, particularly when foraging for nectar or pollen. These observations underscore the mixed pollination system of *P.cerasoides*, involving both ornithophily and entomophily.

Temporal changes in pollinator dominance were documented during the study period. Differences in the identity and activity of dominant pollinators from year to year suggest that *P.cerasoides* relies on a flexible, generalist pollination strategy that may buffer against the effects of annual variation in pollinator populations. The

synchronization between peak anthesis and peak pollinator activity in the morning hours supports the adaptive alignment of floral traits with local environmental conditions and pollinator availability.

The study also evaluated the potential ecological implications of pollinator behavior and visitation frequency. Birds were observed to make direct contact with anthers and stigmas during nectar feeding, facilitating effective pollen transfer. Likewise, insect pollinators often visited multiple flowers within and between trees, contributing to both geitonogamous and xenogamous pollination. Birds and insect visitors were considered effective pollinators when they were observed making direct contact with the reproductive organs of the flowers, such as the stamens and stigma, during nectar or pollen foraging. The interaction between floral morphology and pollinator behaviour was found to be well-matched, particularly in the case of small- to medium-sized passerines and native bees.

Climatic factors such as temperature and humidity influenced flowering behaviour and pollinator visitation patterns. Peak anthesis in both regions occurred during periods of optimal microclimatic conditions. The study recorded a strong relationship between environmental cues and reproductive phenology, emphasizing the importance of local conditions in determining reproductive timing and success. The availability and reliability of pollinators during the flowering period were essential determinants of the fruit set, especially given the partial self-compatibility of the species.

This study provides an integrative understanding of the reproductive ecology of *P. cerasoides* across two contrasting forest environments. The findings affirm that reproductive success in this species is dependent on biotic pollination and that its floral biology is closely aligned with the behaviour of diverse pollinator groups. The observed regional and annual variation in flowering phenology and pollinator assemblages suggests that *P. cerasoides* exhibits ecological plasticity, enabling it to reproduce effectively under varying environmental conditions. These insights contribute valuable knowledge to the fields of plant reproductive biology, pollination

ecology, and conservation, particularly considering changing climate conditions and habitat disturbance.

6.2 Conclusion

This study examined the reproductive ecology of *P. cerasoides* under tropical and temperate forest conditions, focusing on phenological patterns, pollen production, and pollinator availability. Comparative data were collected from field sites in Mizoram and Uttarakhand between 2019-2023.

The phenological study revealed that flowering occurred predominantly during the winter months, with peak anthesis in the early morning. In Mizoram, peak flowering was recorded between 0600–0800 hours, while in Uttarakhand it occurred between 0800–1000 hours. Flowering synchrony and anthesis timing aligned with favorable microclimatic conditions, such as optimal temperature and humidity, supporting increased pollinator activity.

Quantitative assessments of pollen output indicated that *P. cerasoides* produced a substantial amount of viable pollen, necessary for successful fertilization. Anthesis was temperature-dependent, and floral longevity facilitated extended opportunities for pollinator visits.

In both Mizoram and Uttarakhand, *P. cerasoides* exhibited partial self-compatibility, as demonstrated by reduced fruit set under hand self-pollination and autogamy compared to natural and open cross-pollination treatments. Fruit set was highest in naturally pollinated flowers in both regions, followed closely by open cross-pollination, while geitonogamous and self-pollination treatments resulted in comparatively lower success. Apomixis failed to produce fruit in either location, confirming that fertilization in *P. cerasoides* is dependent on effective pollen transfer.

In addition, quantitative analysis revealed that *P. cerasoides* produces a substantial amount of pollen per flower and per tree, indicating its strong reproductive potential.

The high pollen output supports efficient pollen transfer and increases the likelihood of successful fertilization under favourable pollination conditions. *In vitro* pollen germination tests further confirmed that the pollen grains were viable and functionally competent, with consistent germination percentages recorded across multiple years.

Observations of floral visitors across both regions showed a rich diversity of pollinators, a wide variety of visitors, 21 bird species, 6 butterflies, 4 bees and wasps, and even a squirrel were recorded. Among these, birds such as the red-vented bulbul (*Pycnonotus cafer*) and the Indian white-eye (*Zosterops palpebrosus*) played the most crucial roles, frequently contacting stigmas while feeding on nectar. Interestingly, the pollinator communities varied between regions, with a greater diversity of birds in Uttarakhand and more butterfly activity in Mizoram. Yet across both sites, pollinators were most active during mid-morning, matching flower opening times, which suggests a long co-evolutionary relationship between the species and its pollinators. The species appears to be finely adapted to its local climatic conditions, with successful reproduction dependent on the precise alignment of flowering time, temperature, humidity, and pollinator activity. Any disruption to these factors, such as those induced by climate change, may interfere with its reproductive success. Given its reliance on a diverse assemblage of pollinators, particularly birds, the conservation of both the plant and its associated pollinator habitats is essential. The winter flowering of *P. cerasoides* provides a crucial floral resource during a period of general scarcity, thereby supporting a range of faunal species and highlighting its ecological role as a potential keystone species within the ecosystem. This study demonstrates that *P. cerasoides* relied heavily on biotic pollination, particularly ornithophily and entomophily, for reproductive success. Reproductive output was significantly influenced by both pollinator activity and climatic factors affecting anthesis and flower longevity.

The reproductive ecology of *P. cerasoides* is shaped by its floral characteristics, compatibility mechanisms, and interactions with a diverse array of pollinators. Observed regional differences in pollinator assemblages, timing of anthesis, and fruit set reflect the species' ability to adapt to varying environmental conditions. This research contributes valuable ecological insights into this culturally and ecologically

important tree and establishes a basis for future studies. Long-term phenological observations could track the species' response to climate change, while genetic analyses may uncover patterns of gene flow across populations. Additionally, further research on pollinator effectiveness and seed dispersal processes would enhance understanding of the species' reproductive dynamics and resilience. The findings offer essential baseline data to support conservation efforts and sustainable management of *P. cerasoides*.

References

- Abdul-Baki, A. A. (1992). Determination of pollen viability in tomatoes. *Journal of the American Society for Horticultural Science*, 117(3), 473–476.
- Abrol, D. P. (2010). Foraging. In H. R. Hepburn & S. E. Radloff (Eds.), *Honeybees of Asia* (pp. 257–292). Springer Berlin Heidelberg.
- Abrol, D. P. (2012). Non-bee pollinators-plant interaction. In *Pollination biology: Biodiversity conservation and agricultural production* (pp. 265–310). Springer.
- Abu-Asab, M. S., Peterson, P. M., Shetler, S. G., & Orli, S. S. (2001). Earlier plant flowering in spring as a response to global warming in the Washington, DC, area. *Biodiversity & Conservation*, 10(4), 597–612.
- Acar, I., Ak, B. E., & Sarpkaya, K. (2010). Effects of boron and gibberellic acid on in vitro pollen germination of pistachio (*Pistacia vera* L.). *African Journal of Biotechnology*, 9(32), 5126–5130.
- Agnihotri, M. S., & Singh, B. P. (1975). Pollen production and allergenic significance of some grasses around Lucknow. *Journal of Palynology*, 11, 151–154.
- Ahrné, K., Bengtsson, J., & Elmqvist, T. (2009). Bumble bees (*Bombus* spp.) along a gradient of increasing urbanization. *PLoS ONE*, 4(5), e5574.
- Aizen, M. A., & Feinsinger, P. (1994). Forest fragmentation, pollination, and plant reproduction in a Chaco dry forest, Argentina. *Ecology*, 75(2), 330–351.
- Akhtar, T., Aziz, M. A., Naeem, M., Ahmed, M. S., & Bodlah, I. (2018). Diversity and relative abundance of pollinator fauna of canola (*Brassica napus* L. var. Chakwal Sarsoon) with managed *Apis mellifera* L. in Pothwar region, Gujar Khan, Pakistan. *Pakistan Journal of Zoology*, 50(2), 567–573.
- Alarcón, M. L., Roquet, C., & Aldasoro, J. J. (2011). Evolution of pollen/ovule ratios and breeding system in *Erodium* (Geraniaceae). *Systematic Botany*, 36(3), 661–676.
- Albrecht, M., Schmid, B., Hautier, Y., & Müller, C. B. (2012). Diverse pollinator communities enhance plant reproductive success. *Proceedings of the Royal Society B: Biological Sciences*, 279(1748), 4845–4852.

- Aleixo, K. P., de Faria, L. B., Groppo, M., do Nascimento Castro, M. M., & da Silva, C. I. (2014). Spatiotemporal distribution of floral resources in a Brazilian city: Implications for the maintenance of pollinators, especially bees. *Urban Forestry & Urban Greening*, 13(4), 689-696.
- Ali, S. A. (1932). Flower-birds and bird-flowers in India. *Journal of the Bombay Natural History Society*, 35, 573-605.
- Ali, S., & Ripley, S. D. (1999). *Handbook of the birds of India and Pakistan (Vol. 10): Flowerpeckers to buntings* (2nd ed.). Oxford University Press.
- Allen, G., & Davies, R. G. (2022). Canopy sampling reveals hidden potential value of woodland trees for wild bee assemblages. *Insect Conservation and Diversity*, 16(1), 33–46.
- Allison, T. D. (1990). Pollen production and plant density affect pollination and seed production in *Taxus canadensis*. *Ecology*, 71(2), 516-522.
- Aloni, R., Aloni, E., Langhans, M., & Ullrich, C. I. (2006). Role of auxin in regulating *Arabidopsis* flower development. *Planta*, 223, 315-328.
- Ananthakrishnan, T. N. (1982). Thrips and pollination biology. *Current Science*, 51, 168–172.
- Ananthakrishnan, T. N. (1993). The role of thrips in pollination. *Current Science*, 64, 262–264.
- Anderson, J. T., Inouye, D. W., McKinney, A. M., Colautti, R. I., & Mitchell-Olds, T. (2012). Phenotypic plasticity and adaptive evolution contribute to advancing flowering phenology in response to climate change. *Proceedings of the Royal Society B: Biological Sciences*, 279(1743), 3843–3852.
- Anderson, S. H. (2003). The relative importance of birds and insects as pollinators of the New Zealand flora. *New Zealand Journal of Ecology*, 27(2), 83–94.
- Anonymous. (2003). *Mutualism: Lecture 11 outline*. Entomology BIOL 4731.
- Ansari, M., & Davarynejad, G. (2008). The flower phenology of sour cherry cultivars. *American-Eurasian Journal of Agricultural & Environmental Sciences*, 4(1), 117–124.
- Antram, C. B. (1924). *Butterflies of India*. Mittal Publications.
- Appanah, S. (1981). Pollination in Malaysian primary forests. *Malaysian Forester*, 44, 37-42.

- Appanah, S., & Chan, H. T. (1981). Thrips: The pollinators of some dipterocarps. *Malaysian Forester*, 44(2/3), 234–252.
- Armstrong, J. A. (1979). Biotic pollination mechanisms in the Australian flora—a review. *New Zealand Journal of Botany*, 17(4), 467–508.
- Arora, D. S., & Mahajan, H. (2019). Major phytoconstituents of *Prunus cerasoides* responsible for antimicrobial and antibiofilm potential against some reference strains of pathogenic bacteria and clinical isolates of MRSA. *Applied Biochemistry and Biotechnology*, 1-20.
- Arroyo, M. T., Pacheco, D. A., & Dudley, L. S. (2017). Functional role of long-lived flowers in preventing pollen limitation in a high elevation outcrossing species. *AoB Plants*, 9(6), plx050.
- Aslam, M., Brown, M. S., & Kohel, R. J. (1964). Evaluation of seven tetrazolium salts as vital pollen stains in cotton (*Gossypium hirsutum* L.). *Crop Science*, 4, 508–510.
- Augspurger, C. K. (1980). Mass-flowering of a tropical shrub (*Hybanthus prunifolius*): Influence on pollinator attraction and movement. *Evolution*, 34(3), 475-488.
- Augspurger, C. K. (1981). Reproductive synchrony of a tropical shrub: Experimental studies on effects of pollinators and seed predators in *Hybanthus prunifolius* (Violaceae). *Ecology*, 62(3), 775–788.
- Augspurger, C. K. (1983a). Seed dispersal of the tropical tree, *Platypodium elegans*, and the escape of its seedlings from fungal pathogens. *The Journal of Ecology*, 71(3), 759–771.
- Augspurger, C. K. (1983b). Phenology, flowering synchrony, and fruit set of six neotropical shrubs. *Biotropica*, 15(4), 257–267.
- Awasthi, P., Ram, R., Reddy, S. G. E., Nadda, G., Zaidi, A. A., & Hallan, V. (2015). Himalayan wild cherry (*Prunus cerasoides*) as a new natural host of *Cherry necrotic rusty mottle virus* (CNRMV) and a possible role of insect vectors in their transmission. *Annals of Applied Biology*, 166(3), 402-409.
- Ayers, A. C., & Rehan, S. M. (2021). Supporting bees in cities: how bees are influenced by local and landscape features. *Insects*, 12(2), 128.

- Baba Nitsa, M., Balogun, S. T., Odey, F. C., Dada, K. E., Idrisu, M., Ugioro, O., & Oyeledun, K. O. (2020). Evaluation of pollen viability and in vitro pollen germination in relation to different maturity stages of flowers in kola (*Cola nitida*). *Global Scientific Journal (GSJ)*, 8(5).
- Bai, J. A., & Subba Reddi, C. (1980). Pollen productivity and pollen incidence in some potentially allergenic plants of Visakhapatnam. *Advances in Pollen-Spore Research*, 5–7, 217–224.
- Baishnab, B., Paul, S., & Datta, B. K. (2024). Deceptive pollination mechanisms and low natural fruit set in *Cymbidium aloifolium* (L.) Sw. (Orchidaceae). *Research Square*. <https://doi.org/10.21203/rs.3.rs-4430497/v1>
- Baker, H. G., & Baker, I. (1973). Amino-acids in nectar and their evolutionary significance. *Nature*, 241(5391), 543–545.
- Baker, H. G., & Baker, I. (1990). The predictive value of nectar chemistry to the recognition of pollinator types. *Israel Journal of Plant Sciences*, 39(1-2), 157-166.
- Baker, H. G., Bawa, K. S., Frankie, G. W., & Opler, P. A. (1983). Reproductive biology of plants in tropical forests. *Proceedings of the National Academy of Sciences*, 80(16), 5070–5074.
- Baker, J. R., & Baker, I. (1936). The seasons in a tropical rain-forest (New Hebrides). Part 2. Botany. *Zoological Journal of the Linnean Society*, 39(267), 507–519.
- Bakshi, N., Devi, M., & Sharma, H. K. (2018a). Effect of mode of pollination on fruit set and quality of sweet cherry (*Prunus avium* L.) in Kullu Valley of Himachal Pradesh. *Journal of Pharmacognosy and Phytochemistry*, 7(4), 2321–2325.
- Bakshi, N., Devi, M., & Sharma, H. K. (2018b). Studies on pollination efficiency of hive bees and *Episyrphus balteatus* on sweet cherry (*Prunus avium* L.). *Journal of Entomology and Zoology Studies*, 6(4), 1539–1543.
- Baldock, K. C. (2020). Opportunities and threats for pollinator conservation in global towns and cities. *Current Opinion in Insect Science*, 38, 63–71.
- Bandeira e Sousa, M., Andrade, L. R. B. D., Souza, E. H. D., Alves, A. A. C., & de Oliveira, E. J. (2021). Reproductive barriers in cassava: Factors and implications for genetic improvement. *PLOS ONE*, 16(11), e0260576.

- Barendregt, A., Zeegers, T., van Steenis, W., & Jongejans, E. (2022). Forest hoverfly community collapse: Abundance and species richness drop over four decades. *Insect Conservation and Diversity*, 15(5), 510-521.
- Barrett, S. C. H. (1988). The evolution, maintenance, and loss of self-incompatibility systems. In J. Lovett Doust & L. Lovett Doust (Eds.), *Plant reproductive ecology: Patterns and strategies* (pp. 98–124). Oxford University Press.
- Barrett, S. C. H., & Harder, L. D. (2017). The ecology of mating and its evolutionary consequences in seed plants. *Annual Review of Ecology, Evolution, and Systematics*, 48, 23–43.
- Barrow, J. R. (1981). A new concept in assessing cotton pollen germinability. *Crop Science*, 21(3), 441-443.
- Barwise, Y., & Kumar, P. (2020). Designing vegetation barriers for urban air pollution abatement: A practical review for appropriate plant species selection. *npj Climate and Atmospheric Science*, 3(1), 12.
- Bates, A. J., Sadler, J. P., Fairbrass, A. J., Falk, S. J., Hale, J. D., & Matthews, T. J. (2011). Changing bee and hoverfly pollinator assemblages along an urban-rural gradient. *PLOS ONE*, 6(8), e23459.
- Bawa, K. S. (1974). Breeding systems of tree species of a lowland tropical community. *Evolution*, 28(1), 85-92.
- Bawa, K. S. (1983). Patterns of flowering in tropical plants. In C. E. Jones & J. Little (Eds.), *Handbook of experimental pollination biology* (pp. 411–447). Van Nostrand Reinhold.
- Bawa, K. S. (1990). Plant-pollinator interactions in tropical rain forests. *Annual Review of Ecology and Systematics*, 21(1), 399-422.
- Bawa, K. S., & Beach, J. H. (1981). Evolution of sexual systems in flowering plants. *Annals of the Missouri Botanical Garden*, 68(2), 254–274.
- Bawa, K. S., Bullock, S. H., Perry, D. R., Coville, R. E., & Grayum, M. H. (1985). Reproductive biology of tropical lowland rain forest trees. II. Pollination systems. *American Journal of Botany*, 72(3), 346–356.
- Bawa, K. S., Kang, H., & Grayum, M. H. (2003). Relationships among time, frequency, and duration of flowering in tropical rain forest trees. *American Journal of Botany*, 90(6), 877-887.

- Beattie, A. J., Turnbull, C., Knox, R. B., & Williams, E. G. (1984). Ant inhibition of pollen function: A possible reason why ant pollination is rare. *American Journal of Botany*, 71(3), 421–426.
- Becerra, L. X., & Lloyd, D. G. (1992). Competition-dependent abscission of self-pollinated flowers of *Phormium tenax* (Agavaceae): A second action of self-incompatibility at the whole flower level? *Evolution*, 46(2), 458-469.
- Bennet, S. J. (2001). Pollen-ovule ratios as a method of estimating breeding system in *Trifolium* pasture species. In *Proceedings of the 10th Australian Agronomy Conference*, Hobart, Australia.
- Bera, S. K. (1990). Palynology of *Shorea robusta* (Dipterocarpaceae) in relation to pollen production and dispersal. *Grana*, 29(3), 251-255.
- Bernardello, G., Anderson, G. J., Stuessy, T. F., & Crawford, D. J. (2001). A survey of floral traits, breeding systems, floral visitors, and pollination systems of the angiosperms of the Juan Fernández Islands (Chile). *The Botanical Review*, 67(3), 255-308.
- Bernardello, G., Anderson, G. J., Stuessy, T. F., & Crawford, D. J. (2006). The angiosperm flora of the Archipelago Juan Fernández (Chile): Origin and dispersal. *Canadian Journal of Botany*, 84(9), 1266–1281.
- Bertin, R. I. (1989). Pollination biology. In W. G. Abrahamson (Ed.), *Plant-animal interactions* (pp. 23–86). McGraw-Hill.
- Bertrand, C., Eckert, P. W., Ammann, L., Entling, M. H., Gobet, E., Herzog, F., & Albrecht, M. (2019). Seasonal shifts and complementary use of pollen sources by two bees, a lacewing and a ladybeetle species in European agricultural landscapes. *Journal of Applied Ecology*, 56(11), 2431–2442.
- Bhandal, I. S., & Malik, C. P. (1979). Effect of gibberellic acid, (2-chloroethyl) phosphonic acid, actinomycin-D, and cycloheximide on the activity and leaching of some hydrolases in pollen suspension cultures of *Crotalaria juncea*. *Physiologia Plantarum*, 45(3), 297–300.
- Bhatt, A. (2024). A study of the unexplored cuisine of Uttarakhand and its role in culinary tourism promotion. *International Journal of Tourism and Hotel Management*, 6(1), 1–7.

- Bhattacharya, A., & Mandal, S. (2000). Pollination biology in *Bombax ceiba* Linn. *Current Science*, 79(12), 1706–1712.
- Biesmeijer, J. C., Roberts, S. P., Reemer, M., Ohlemüller, R., Edwards, M., Peeters, T., & Kunin, W. E. (2006). Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science*, 313(5785), 351–354.
- Bishop, J. G., & Schemske, D. W. (1998). Variation in flowering phenology and its consequences for lupines colonizing Mount St. Helens. *Ecology*, 79(2), 534–546.
- Blando, F., Gerardi, C., & Nicoletti, I. (2004). Sour cherry (*Prunus cerasus* L.) anthocyanins as ingredients for functional foods. *BioMed Research International*, 2004(5), 253–258.
- Bond, W. J. (1994). Do mutualisms matter? Assessing the impact of pollinator and disperser disruption on plant extinction. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 344(1307), 83–90.
- Bonofiglio, T., Orlandi, F., Ruga, L., Romano, B., & Fornaciari, M. (2013). Climate change impact on the olive pollen season in Mediterranean areas of Italy: Air quality in late spring from an allergenic point of view. *Environmental Monitoring and Assessment*, 185(2), 877–890.
- Borchert, R., Meyer, S. A., Felger, R. S., & Porter-Bolland, L. (2004). Environmental control of flowering periodicity in Costa Rican and Mexican tropical dry forests. *Global Ecology and Biogeography*, 13(5), 409–425.
- Bosch, M., Simon, J., Molero, J., & Blanche, C. (2001). Breeding systems in tribe Delphinieae (Ranunculaceae) in the western Mediterranean area. *Flora*, 196(1), 101–113.
- Bown, D. (1995). *The Royal Horticultural Society encyclopedia of herbs and their uses*. Dorling Kindersley Limited.
- Brandenburg, A., Dell’Olivo, A., Bshary, R., & Kuhlemeier, C. (2009). The sweetest thing: Advances in nectar research. *Current Opinion in Plant Biology*, 12(4), 486–490.
- Branscheidt, P. (1930). Zur Physiologie der Pollenkeimung und ihrer experimentellen Beeinflussung. *Planta*, 11(2), 368–456.

- Brantjes, N. B. M., & Leemans, J. A. A. M. (1976). *Silene otites* (Caryophyllaceae) pollinated by nocturnal Lepidoptera and mosquitoes. *Acta Botanica Neerlandica*, 25(4), 281–295.
- Brewbaker, J. L., & Majumdar, S. K. (1961). Cultural studies on the pollen population effect and the self-incompatibility inhibition. *American Journal of Botany*, 48(4), 457–464.
- Brewbaker, J. L., & Kwack, B. H. (1963). The essential role of calcium ion in pollen germination and pollen tube growth. *American Journal of Botany*, 50(9), 859–865.
- Brittain, C. A., Vighi, M., Bommarco, R., Settele, J., & Potts, S. G. (2010). Impacts of a pesticide on pollinator species richness at different spatial scales. *Basic and Applied Ecology*, 11(2), 106–115.
- Brittain, C., & Potts, S. G. (2011). The potential impacts of insecticides on the life-history traits of bees and the consequences for pollination. *Basic and Applied Ecology*, 12(4), 321–331.
- Bronstein, J. L., & Hossaert-McKey, M. (1995). Hurricane Andrew and a Florida fig pollination mutualism: Resilience of an obligate interaction. *Biotropica*, 27(4), 373–381.
- Brown, B. J., Mitchell, R. J., & Graham, S. A. (2002). Competition for pollination between an invasive species (purple loosestrife) and a native congener. *Ecology*, 83(8), 2328–2336.
- Brown, J. H., & Kodric-Brown, A. (1979). Convergence, competition, and mimicry in a temperate community of hummingbird-pollinated flowers. *Ecology*, 60(5), 1022–1035.
- Bullock, S. H. (1985). Breeding systems in the flora of a tropical deciduous forest in Mexico. *Biotropica*, 17(4), 287–301.
- Bullock, S. H., & Bawa, K. S. (1981). Sexual dimorphism and the annual flowering pattern in *Jacaratiadolichaula* (D. Smith) Woodson (Caricaceae) in a Costa Rican rain forest. *Ecology*, 62(6), 1494–1504.
- Burd, M. (1994). Bateman's principle and plant reproduction: The role of pollen limitation in fruit and seed set. *The Botanical Review*, 60(1), 83–139.

- Burd, M. (2011). Are relationships between pollen–ovule ratio and pollen and seed size explained by sex allocation? *Evolution: International Journal of Organic Evolution*, 65(10), 3002–3005.
- Burgos, L., Petri, C., &Badenes, M. L. (2007). *Prunus spp.* In T. Nagata & H. Lörz (Eds.), *Biotechnology in Agriculture and Forestry* (Vol. 250, pp. 283–315). Springer.
- Burkett, D. A. (1998). *Light color attraction and dietary sugar composition for several mosquito (Diptera: Culicidae) species found in north central Florida*. University of Florida.
- Burkle, L. A., Marlin, J. C., & Knight, T. M. (2013). Plant–pollinator interactions over 120 years: Loss of species, co-occurrence, and function. *Science*, 339(6127), 1611–1615.
- Butcher, P. A., Bradbury, D., & Krauss, S. L. (2011). Limited pollen-mediated dispersal and partial self-incompatibility in the rare ironstone endemic *Tetralochea paynterae* subsp. *paynterae* increase the risk associated with habitat loss. *Conservation Genetics*, 12, 1603–1618.
- Campbell, D. R., &Halama, K. J. (1993). Resource and pollen limitations to lifetime seed production in a natural plant population. *Ecology*, 74(4), 1043-1051.
- Cane, J. H. (2016). Adult pollen diet essential for egg maturation by a solitary *Osmia* bee. *Journal of Insect Physiology*, 95, 105-109.
- Casper, B. B. (1988). Evidence for selective embryo abortion in *Cryptantha flava*. *The American Naturalist*, 132(3), 318-326.
- Castiñeiras, P., Vázquez-Ruiz, R. A., Fernández-González, M., Rodríguez-Rajo, F. J., & Aira, M. J. (2019). Production and viability of *Fraxinus* pollen and its relationship with aerobiological data in the northwestern Iberian Peninsula. *Aerobiologia*, 35, 227-241.
- Cerdán, P. D., &Chory, J. (2003). Regulation of flowering time by light quality. *Nature*, 423(6942), 881-885.
- Champion, H. G., & Seth, S. K. (1968). *A revised survey of the forest types of India*. Government of India Press.

- Chan, Y. M., Lim, A. L., & Saw, L. G. (2011). Reproductive biology of the endangered and endemic palm *Johannesteijsmannia lanceolata* (Arecaceae). *Journal of Tropical Forest Science*, 23(2), 213–221.
- Chand, V. P., Sukumaran, A., & Khanduri, V. P. (2022). Reproductive phenology and floral visitors in *Rhododendron arboreum* (Ericaceae) in a temperate forest of Garhwal Himalaya. *Plant Ecology & Evolution*, 155(1), 56–65.
- Chang, J. J., Crall, J. D., & Combes, S. A. (2016). Wind alters landing dynamics in bumblebees. *Journal of Experimental Biology*, 219(18), 2819–2822.
- Charlesworth, D., & Charlesworth, B. (1987). Inbreeding depression and its evolutionary consequences. *Annual Review of Ecology and Systematics*, 18(1), 237–268.
- Chatterjee, A., & Pakrashi, S. C. (1991). *The treatise on Indian medicinal plants* (Vol. 6). National Institute of Science Communication and Information Resources, CSIR.
- Chauhan, S. (2019). Phenology, floral biology and breeding system of loquat (*Eriobotrya japonica* (Thunb.) Lindl.) (Rosaceae). *Plant Reproductive Biology*, 31(2), 135–143.
- Chauhan, Y. S., & Katiyar, S. R. (1997). Studies on the reproductive biology of *Schima*. I. Pollen germination in *S. wallichii* (DC) Korth. *Journal of Tree Science*, 15, 76–81.
- Cheke, R. A., Mann, C. F., & Allen, R. (2001). *Sunbirds: A guide to the sunbirds, flowerpeckers, spiderhunters and sugarbirds of the world*. Yale University Press.
- Chen, J. C., & Fang, S. C. (2016). The long pollen tube journey and in vitro pollen germination of *Phalaenopsis* orchids. *Plant Reproduction*, 29(2), 179–188.
- Chettri, N., & Sharma, E. (2009). A scientific assessment of traditional knowledge on firewood and fodder values in Sikkim, India. *Forest Ecology and Management*, 257(10), 2073–2078.
- Chhun, T., Aya, K., Asano, K., Yamamoto, E., Morinaka, Y., Watanabe, M., & Ueguchi-Tanaka, M. (2007). Gibberellin regulates pollen viability and pollen tube growth in rice. *The Plant Cell*, 19(12), 3876–3888.

- Christensen, J. V. (1996). Flowering period of 175 sweet cherry cultivars with regard to cross-pollination possibilities. *Acta Horticulturae*, 423, 39–48.
- Chuine, I. (2010). Why does phenology drive species distribution? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1555), 3149–3160.
- Cleland, E. E., Chuine, I., Menzel, A., Mooney, H. A., & Schwartz, M. D. (2007). Shifting plant phenology in response to global change. *Trends in ecology & evolution*, 22(7), 357–365.
- Colasanti, J., & Coneva, V. (2009). Mechanisms of floral induction in grasses: something borrowed, something new. *Plant Physiology*, 149(1), 56–62.
- Collin, C. L., & Shykoff, J. A. (2010). Flowering phenology and female fitness: impact of a pre-dispersal seed predator on a sexually polymorphic species. *Plant Ecology*, 206, 1–13.
- Conrad, T., Stöcker, C., & Ayasse, M. (2017). The effect of temperature on male mating signals and female choice in the red mason bee, *Osmia bicornis* (L.). *Ecology and Evolution*, 7(21), 8966–8975.
- Cook, S. A., & Stanley, R. G. (1960). Tetrazolium chloride as an indicator of pine pollen germinability. *Silvae Genetica*, 9, 134–136.
- Corlett, R. T. (2004). Flower visitors and pollination in the Oriental (Indomalayan) Region. *Biological Reviews*, 79(3), 497–532.
- Cortés-Flores, J., Hernández-Esquivel, K. B., González-Rodríguez, A., & Ibarra-Manríquez, G. (2017). Flowering phenology, growth forms, and pollination syndromes in tropical dry forest species: Influence of phylogeny and abiotic factors. *American Journal of Botany*, 104(1), 39–49.
- Cour, P., & Van Campo, M. (1980). Previsions de récoltes a partir de l'analyse du contenu pollinique de l'atmosphère [intensité de la pollinisation]. *Comptes Rendus Hebdomadaires des Seances de l'Académie des Sciences. Serie D*, 290.
- Craine, J. M., Wolkovich, E. M., & Towne, E. G. (2012b). The roles of shifting and filtering in generating community-level flowering phenology. *Ecography*, 35(11), 1033–1038.

- Craine, J. M., Wolkovich, E. M., Gene Towne, E., & Kembel, S. W. (2012a). Flowering phenology as a functional trait in a tallgrass prairie. *New phytologist*, 193(3), 673-682.
- Cranbrook, E., & Furtado, J. I. (1988). *Key environments: Malaysia* (pp. 1-317). Pergamon Press.
- Crane, E., Walker, P., & Day, R. (1984). *Directory of important world honey sources*. International Bee Research Association.
- Cronk, Q., & Ojeda, I. (2008). Bird-pollinated flowers in an evolutionary and molecular context. *Journal of Experimental Botany*, 59(4), 715–727.
- Cruden, R. W. (1977). Pollen-ovule ratios: A conservative indicator of breeding systems in flowering plants. *Evolution*, 31(1), 32–46.
- Cruden, R. W. (1988). Temporal dioecism: Systematic breadth, associated traits, and temporal patterns. *Botanical Gazette*, 149(1), 1–15.
- Cruden, R. W. (2000). Pollen grains: Why so many? *Plant Systematics and Evolution*, 222(1-4), 143–165.
- Cruden, R. W., & Hermann-Parker, S. M. (1977). Temporal dioecism: An alternative to dioecism. *Evolution*, 31(4), 863–866.
- Cruden, R. W., & Lyon, D. L. (1985). Patterns of biomass allocation to male and female functions in plants with different mating systems. *Oecologia*, 66, 299–306.
- Cruden, R. W., & Lyon, D. L. (2019). Facultative xenogamy: Examination of a mixed mating system. In *The evolutionary ecology of plants* (pp. 171–207). CRC Press.
- Cunningham, S. A. (2000). Depressed pollination in habitat fragments causes low fruit set. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 267(1448), 1149-1152.
- Dafni, A. (1992). *Pollination ecology: A practical approach*. Oxford University Press.
- Dafni, A., & Firmage, D. (2000). Pollen viability and longevity: Practical, ecological and evolutionary implications. *Plant Systematics and Evolution*, 222(1–4), 113–132.

- Dahiya, O. S. (1995). Pollen viability and stigma receptivity in relation to meteorological parameters in pearl millet. *Seed Science and Technology*, 23(1), 147–156.
- Damialis, A., Fotiou, C., Halley, J. M., & Vokou, D. (2011). Effects of environmental factors on pollen production in anemophilous woody species. *Trees*, 25(2), 253–264.
- Danforth, B. (2007). Bees. *Current Biology*, 17(5), R156-R161.
- Dar, S. A., Lone, G. M., Parey, S. H., Hassan, G. I., & Rather, B. A. (2017a). Insect pollinators and their conservation. *Journal of Entomology and Zoology Studies*, 5(3), 1121-1131.
- Dar, S. A., Mir, G. M., Parry, M. A., Ahmad, S. B., Ganie, M. A., Raja, T. A., & Parry, S. H. (2016). Diversity and richness indices and the Whittaker plot value of insect pollinators of peach *Prunus persica* in landscapes of temperate India. *Academic Journal of Entomology*, 9(4), 62-73.
- Dar, S. A., Mir, G. M., Parry, M. A., Parry, S. H., Yaqob, M., & Khrusheed, R. (2017b). Potential habitat value for wild bees in Kashmir valley. *Journal of Crop and Weed*, 13(1), 125-131.
- Dar, S. A., Mir, S. H., & Rather, B. A. (2017c). Importance of hedgerows for wild bee abundance and richness in Kashmir Valley. *Entomon*, 42(1), 59-68.
- Dar, S. A., Wani, S. H., Javeed, K., Mir, S. H., Yaqoob, M., Showkat, A., & Farook, U. B. (2020a). Foraging behaviour, abundance and rank abundance of insect pollinators on plum crop (*Prunus domestica*) in Himalayan regions. *Journal of Entomology and Zoology Studies*, 8(6), 575–582.
- Dar, S. A., Wani, S. H., Javeed, K., Mir, S. H., Yaqoob, M., Showkat, A., & Islam, T. (2020b). Mountain landscapes, foraging behaviour and visitation frequencies of insect pollinators on peach (*Prunus persica*). *International Journal of Chemical Studies*, 8(6), 42–49.
- Das, B. K. (2019). State of economics of education: A study of Mizoram. *Society & Change*, 13(3). ISSN: 1997-1052 (Print), 2227-202X (Online).
- Das, P. K. (2013). “The Himalayan tsunami” – Cloudburst, flash flood & death toll: A geographical postmortem. *IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)*, 7(2), 33–45.

- Davidar, P. (1985). Ecological interactions between mistletoes and their avian pollinators in South India. *Journal of the Bombay Natural History Society*, 82(1), 45–60.
- Davies, T. J., Wolkovich, E. M., Kraft, N. J., Salamin, N., Allen, J. M., Ault, T. R., & Travers, S. E. (2013). Phylogenetic conservatism in plant phenology. *Journal of Ecology*, 101(6), 1520–1530.
- Davis, A., Major, R. E., & Taylor, C. E. (2015). The association between nectar availability and nectarivore density in urban and natural environments. *Urban Ecosystems*, 18, 503–515.
- Dayanandan, S., Attygalla, D. N. C., Abeygunasekera, A. W. W. L., Gunatilleke, I. A. U. N., & Gunatilleke, C. V. S. (1990). Phenology and floral morphology in relation to pollination of some Sri Lankan dipterocarps. In *Reproductive Ecology of Tropical Forest Plants* (Vol. 7, pp. 103–133).
- De Nettancourt, D. (1997). Incompatibility in angiosperms. *Sexual Plant Reproduction*, 10(4), 185–199.
- De Vries, P. J. (1979). Pollen-feeding rain forest *Parides* and *Battus* butterflies in Costa Rica. *Biotropica*, 11(3), 237–238.
- Devlin, B., Horton, J. B., & Stephenson, A. G. (1987). Patterns of nectar production of *Lobelia cardinalis*. *American Midland Naturalist*, 118(2), 289–295.
- Devy, M. S., & Davidar, P. (2003). Pollination systems of trees in Kakachi, a mid-elevation wet evergreen forest in Western Ghats, India. *American Journal of Botany*, 90(4), 650–657.
- Devy, M. S., & Livingstone, C. (2001). Interactions between social bees and their food plants in a rainforest canopy of Western Ghats, India. In K. N. Ganeshaiah, R. U. Shaanker, & K. S. Bawa (Eds.), *Tropical ecosystems: Structure, diversity and human welfare* (pp. 420–422). Oxford & IBH Publishing, New Delhi, India.
- Dhar, M. L., Dhar, M. M., Dhawan, B. N., Mehrotra, B. N., & Ray, C. (1968). Screening of Indian plants for biological activity: Part I. *Indian Journal of Experimental Biology*, 6(3), 232–247.

- Dhiman, J. (2014). *Studies on reproductive biology of wild pomegranate (Punica granatum L.)* (Doctoral dissertation, Dr. YS Parmar University of Horticulture and Forestry, Nauni).
- Dhiman, P. (2024). Diversity, distribution and relative abundance of different insect pollinators of peach in different regions of Western Himalaya. In N. Kumari, S. Sharma, N. Kumar, & H. S. Banyal (Eds.), *Insect pollinators diversity: Distribution, ecological function and conservation status in Himalayan region* (pp. 248–249). Bharti Publications.
- Dmitruk, M. E., Chrzanowska, E., Strzalkowska-Abramek, M., & Stawiarz, E. (2023). *Prunus spinosa* L. pollen-quantity and nutritional quality. *Acta Agrobotanica*, 76.
- Dodd, M. E., Silvertown, J., & Chase, M. W. (1999). Phylogenetic analysis of trait evolution and species diversity variation among angiosperm families. *Evolution*, 53(3), 732-744.
- Dongariyal, A., Dimri, D. C., Kumar, P., Choudhary, A., Jat, P. K., Basile, B., Mataffo, A., Corrado, G., & Singh, A. (2022). Pollen-pistil interaction in response to pollination variants in subtropical Japanese plum (*Prunus salicina* Lindl.) varieties. *Plants*, 11(22), 3081.
- Du, Y., Mao, L., Queenborough, S. A., Freckleton, R. P., Chen, B., & Ma, K. (2015). Phylogenetic constraints and trait correlates of flowering phenology in the angiosperm flora of China. *Global Ecology and Biogeography*, 24(8), 928–938.
- Duan, X. M. (2003). A study on soft cutting of *Cerasus cerasoides*. *Journal of the Southwest Forestry College*, 23(1), 43-45.
- Duan, X. M., & Fan, G. S. (2004). Study on community characteristics of *Cerasus cerasoides*. *Journal of Southwest Forestry University*, 24(1), 15-19.
- Dukas, R., & Morse, D. H. (2003). Crab spiders affect flower visitation by bees. *Oikos*, 101(1), 157–163.
- Dyer, A. G., Whitney, H. M., Arnold, S. E., Glover, B. J., & Chittka, L. (2006). Bees associate warmth with floral colour. *Nature*, 442(7102), 525-525.
- Easterling, D. R., Evans, J. L., Groisman, P. Y., Karl, T. R., Kunkel, K. E., & Ambenje, P. (2000). Observed variability and trends in extreme climate

- events: A brief review. *Bulletin of the American Meteorological Society*, 81(3), 417-426.
- Edlund, A. F., Swanson, R., & Preuss, D. (2004). Pollen and stigma structure and function: The role of diversity in pollination. *The Plant Cell*, 16(suppl_1), S84-S97.
- Egea, J., Burgos, L., Garcia, J. E., & Egea, L. (1991). Stigma receptivity and style performance in several apricot cultivars. *Journal of Horticultural Science*, 66(1), 19–25.
- Elzinga, J. A., Atlan, A., Biere, A., Gigord, L., Weis, A. E., & Bernasconi, G. (2007). Time after time: Flowering phenology and biotic interactions. *Trends in Ecology & Evolution*, 22(8), 432-439.
- Elzinga, J. A., Atlan, A., Biere, A., Gigord, L., Weis, A. E., & Bernasconi, G. (2007). Time after time: Flowering phenology and biotic interactions. *Trends in Ecology & Evolution*, 22(8), 432–439.
- Epps, M. J., Allison, S. E., & Wolfe, L. M. (2015). Reproduction in flame azalea (*Rhododendron calendulaceum*, Ericaceae): A rare case of insect wing pollination. *The American Naturalist*, 186(2), 294-301.
- Erdtman, G. (1943). Pollenspektra från svenska växtsamhällen jämte pollenanalytiska markstudier i södra Lappland. *Geologiska Föreningen i Stockholm Förhandlingar*, 65(1), 37–66.
- Erdtman, G. (1954a). *An Introduction to Pollen Analysis* (239 pp.). Chronica Botanica Co.
- Erdtman, G. (1954b). Pollen morphology and plant taxonomy. *BotaniskaNotiser*, 107, 65-81.
- Erfani, M., Miri, S. M., & Imani, A. (2017). In vitro shoot proliferation and rooting of Garnem rootstock as influenced by basal media, plant growth regulators, and carbon sources. *Plant Cell Biotechnology and Molecular Biology*, 18(3–4), 101–109.
- Eriksson, O. (1987). Regulation of seed-set and gender variation in the hermaphroditic plant *Potentilla anserina*. *Oikos*, 48(2), 165–171.
- Etcheverry, A. V., Aleman, M. M., Figueroa-Fleming, T., López-Spahr, D., Gomez, C. A., Yanez, C., & Ortega-Baes, P. (2012). Pollen: Ovule ratio and its

- relationship with other floral traits in *Papilionoideae* (Leguminosae): An evaluation with Argentine species. *Plant Biology*, 14(1), 171–178.
- Fadón, E., Herrero, M., & Rodrigo, J. (2015). Flower development in sweet cherry framed in the BBCH scale. *Scientia Horticulturae*, 192, 141–147.
- Fægri, K. (1956). Recent trends in palynology. *Botanical Review*, 22(9), 639–664.
- Fægri, K. (1978). Trends in research in pollination ecology. *The Botanical Review*, 44(1), 1–45.
- Fægri, K., & Iversen, J. (1950). *Textbook of Modern Pollen Analysis*. EjnarMunksgaard.
- Fægri, K., & Iversen, J. (1964). *Textbook of Pollen Analysis* (2nd rev. ed.). Hafner Publishing Co.
- Fægri, K., & Iversen, J. (1989). *Textbook of pollen analysis* (revised by Fægri, K., Kaland, P. E., & Krzywinski, K.). Wiley.
- Fægri, K., & Van der Pijl, L. (1979). *The Principles of Pollination Ecology* (3rd ed.). Pergamon Press.
- Fægri, K., & Van der Pijl, L. (2013). *Principles of Pollination Ecology* (4th ed.). Elsevier.
- Faheem, M., Aslam, M., & Razaq, M. (2004). Pollination ecology with special reference to insects: A review. *Journal of Research Science*, 4(1), 395–409.
- Faheem, M., Aslam, M., & Razaq, M. (2004). Pollination ecology with special reference to insects: A review. *Journal of Research (Science)*, Bahauddin Zakariya University, 15(4), 395–409.
- Fang, H. T. (2007). Blossom character and insect pollination of *Prunus mongolica* Maxim. *Chinese Journal of Ecology*, 26(2), 177.
- Faust, M., Timon, B., Surányi, D., Nyujtó, F., & Gradziel, T. M. (2011). *Origin and dissemination of Prunus crops: Peach, cherry, apricot, plum, and almond*. International Society for Horticultural Science (ISHS).
- Feng, B., Li, W., Wei, Y., Xu, Y., & Wang, M. (2016). The flowering biology of plum (*Prunus domestica* L.) in Aksu region, Xinjiang. *Agricultural Science & Technology*, 17(6), 1371–1375.
- Fenner, M. (1998). The phenology of growth and reproduction in plants. *Perspectives in Plant Ecology, Evolution and Systematics*, 1(1), 78–91.

- Fernández-Rodríguez, S., Durán-Barroso, P., Silva-Palacios, I., Tormo-Molina, R., Maya-Manzano, J. M., & Gonzalo-Garijo, Á. (2016). Regional forecast model for the *Olea* pollen season in Extremadura (SW Spain). *International Journal of Biometeorology*, 60, 1509-1517.
- Ferrara, G., Camposeo, S., Palasciano, M., & Godini, A. (2007). Production of total and stainable pollen grains in *Olea europaea* L. *Grana*, 46(2), 85-90.
- Fitter, A. H., & Fitter, R. S. R. (2002). Rapid changes in flowering time in British plants. *Science*, 296(5573), 1689-1691.
- Fleming, T. H., & Muchhala, N. (2008). Nectar-feeding bird and bat niches in two worlds: pantropical comparisons of vertebrate pollination systems. *Journal of Biogeography*, 35(5), 764-780.
- Fleming, T. H., Breitwisch, R., & Whitesides, G. H. (1987). Patterns of tropical vertebrate frugivore diversity. *Annual Review of Ecology and Systematics*, 18(1), 91-109.
- Fleming, T. H., Geiselman, C., & Kress, W. J. (2009). The evolution of bat pollination: a phylogenetic perspective. *Annals of Botany*, 104(6), 1017-1043.
- Fontaine, C., Dajoz, I., Meriguet, J., & Loreau, M. (2006). Functional diversity of plant-pollinator interaction webs enhances the persistence of plant communities. *PLoS Biology*, 4(1), e1.
- Forister, M. L., McCall, A. C., Sanders, N. J., Fordyce, J. A., Thorne, J. H., O'Brien, J., Waetjen, D. P., & Shapiro, A. M. (2010). Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. *Proceedings of the National Academy of Sciences of the United States of America*, 107(5), 2088-2092.
- Forrest, J., & Miller-Rushing, A. J. (2010). Toward a synthetic understanding of the role of phenology in ecology and evolution. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1555), 3101-3112.
- Frankie, G. W., Baker, H. G., & Opler, P. A. (1974a). Comparative phenological studies of trees in tropical wet and dry forests in the lowlands of Costa Rica. *Journal of Ecology*, 62(3), 881-919.

- Frankie, G. W., Baker, H. G., & Opler, P. A. (1974b). Tropical plant phenology: Applications for studies in community ecology. In H. Lieth (Ed.), *Phenology and seasonality modeling* (pp. 287–296). Springer Berlin Heidelberg.
- Frankie, G. W., Vinson, S. B., Rizzardi, M. A., Griswold, T. L., Coville, R. E., Grayum, M. H., & Pawelek, J. C. (2013). Relationships of bees to host ornamental and weedy flowers in urban Northwest Guanacaste Province, Costa Rica. *Journal of the Kansas Entomological Society*, 86(4), 325-351.
- Franks, S. J. (2011). Plasticity and evolution in drought avoidance and escape in the annual plant *Brassica rapa*. *New Phytologist*, 190(1), 249-257.
- Friedman, J., & Barrett, S. C. (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.
- Fryxell, P. A. (1957). Mode of reproduction of higher plants. *The Botanical Review*, 23(3), 135-233.
- Gaaliche, B., Majdoub, A., Trad, M., & Mars, M. (2013). Assessment of pollen viability, germination, and tube growth in eight Tunisian caprifig (*Ficus carica* L.) cultivars. *International Scholarly Research Notices*, 2013(1), 207434.
- Galen, C., & Gregory, T. (1989). Interspecific pollen transfer as a mechanism of competition: Consequences of foreign pollen contamination for seed set in the alpine wildflower, *Polemonium viscosum*. *Oecologia*, 81, 120-123.
- Gallardo, R., Dominguez, E., & Muñoz, J. M. (1994). Pollen–ovule ratio, pollen size, and breeding system in *Astragalus* (Fabaceae) subgenus *Epiglottis*: A pollen and seed allocation approach. *American Journal of Botany*, 81(12), 1611–1619.
- Galloni, M., Podda, L., Vivarelli, D., & Cristofolini, G. (2007). Pollen presentation, pollen-ovule ratios, and other reproductive traits in Mediterranean legumes (Fam. Fabaceae-Subfam. Faboideae). *Plant Systematics and Evolution*, 266(3), 147–164.
- Gaur, R. D., & Nanwani, P. (1989). A melittopalynological analysis of apiary honeys from Pauri Garhwal, UP, India. *Indian Bee Journal*, 51(1), 12-14.

- Geber, M. A., & Moeller, D. A. (2006). Pollinator responses to plant communities and implications for reproductive character evolution. In L. D. Harder & S. C. H. Barrett (Eds.), *Ecology and evolution of flowers* (pp. 102-119). Oxford University Press.
- Gencer, C. D., Özkaya, M. T., Eti, S., Karabıyık, Ş., & Fletcher, N. T. M. (2023). Pollen viability and germination levels with amount of pollen production of some important olive cultivars in Türkiye. *Turkish Journal of Agriculture–Food Science and Technology*, 11(6), 1176–1182.
- Geslin, B., Gauzens, B., Thébault, E., & Dajoz, I. (2013). Plant-pollinator networks along a gradient of urbanisation. *PloS One*, 8(5), e63421.
- Gharaghani, A., Solhjoo, S., & Oraguzie, N. (2017). A review of genetic resources of almonds and stone fruits (*Prunus* spp.) in Iran. *Genetic Resources and Crop Evolution*, 64(8), 1767-1780.
- Ghazoul, J. (2005). Buzziness as usual? Questioning the global pollination crisis. *Trends in Ecology & Evolution*, 20(7), 367-373.
- Ghazoul, J., & Shaanker, R. U. (2004). Sex in space: Pollination among spatially isolated plants. *Biotropica*, 36(2), 128-130.
- Ghazoul, J., Liston, K. A., & Boyle, T. J. B. (1998). Disturbance-induced density-dependent seed set in *Shorea siamensis* (Dipterocarpaceae), a tropical forest tree. *Journal of Ecology*, 86(3), 462-473.
- Giannini, T. C., Boff, S., Cordeiro, G. D., Cartolano, E. A., Veiga, A. K., Imperatriz-Fonseca, V. L., & Saraiva, A. M. (2015). Crop pollinators in Brazil: A review of reported interactions. *Apidologie*, 46(2), 209–223.
- Gilbert, L. E. (1972). Pollen feeding and reproductive biology of *Heliconius* butterflies. *Proceedings of the National Academy of Sciences*, 69(6), 1403–1407.
- Ginoya, A. V., Patel, J. B., & Delvadiya, I. R. (2022). *In vitro* pollen germination and pollen viability study in brinjal. *International Journal of Chemical Studies*, 10(1), 1591–1594.
- Gogoi, A., Ahirwal, J., & Sahoo, U. K. (2022). Evaluation of ecosystem carbon storage in major forest types of Eastern Himalaya: Implications for carbon sink management. *Journal of Environmental Management*, 302, 113972.

- Gomez, J. M. (1993). Phenotypic selection on flowering synchrony in a high mountain plant, *Hormathophylla spinosa* (Cruciferae). *Journal of Ecology*, 81(4), 605–613.
- Goodwillie, C., Kalisz, S., & Eckert, C. G. (2005). The evolutionary enigma of mixed mating systems in plants: Occurrence, theoretical explanations, and empirical evidence. *Annual Review of Ecology, Evolution, and Systematics*, 36, 47–79.
- Gottsberger, G. (1974). The structure and function of the primitive angiosperm flower – A discussion. *Acta Botanica Neerlandica*, 23(4), 461–471.
- Gottsberger, G. (1977). Some aspects of beetle pollination in the evolution of flowering plants. In K. Kubitzki (Ed.), *Flowering plants: Evolution and classification of higher categories: Symposium, Hamburg, September 8–12, 1976* (pp. 211–226). Vienna: Springer Vienna.
- Gottsberger, G. (1986). Floral ecology: Report on the years 1981 (79) to 1985. In H.-D. Behnke, K. Esser, K. Kubitzki, M. Runge, & H. Ziegler (Eds.), *Progress in Botany* (Vol. 47, pp. 384–417). Springer-Verlag Berlin Heidelberg.
- Gottsberger, G. (1989). Floral ecology: Report on the years 1985 (1984) to 1988. In P. H. R. G. Müller (Ed.), *Progress in Botany: Structural Botany, Physiology, Genetics, Taxonomy, Geobotany / Fortschritte der Botanik Struktur, Physiologie, Genetik, Systematik, Geobotanik* (pp. 352–379). Springer Berlin Heidelberg.
- Gottsberger, G. (1990). Flowers and beetles in the South American tropics. *Botanica Acta*, 103(4), 360–365.
- Götzenberger, L., Durka, W., Kühn, I., & Klotz, S. (2006). The relationship of pollen-ovule ratio and seed size: A comparative test of a sex allocation hypothesis. *Evolutionary Ecology Research*, 8, 1101–1116.
- Goulson, D., Peat, J., Stout, J. C., Tucker, J., Darvill, B., Derwent, L. C., & Hughes, W. O. (2002). Can alloethism in workers of the bumblebee, *Bombus terrestris*, be explained in terms of foraging efficiency? *Animal Behaviour*, 64(1), 123–130.
- Gradziel, T. M. (2022). Transfer of self-fruitfulness to cultivated almond from peach and wild almond. *Horticulturae*, 8(10), 965.
- Grae, I. (1974). *Nature's colors: Dyes from plants*. Macmillan Publishing Co.

- Grant, V., & Grant, K. A. (1965). *Flower pollination in the Phlox family* (Vol. 399). Columbia University Press.
- Gross, R. S., & Werner, P. A. (1983). Relationships among flowering phenology, insect visitors, and seed set of individuals: Experimental studies on four co-occurring species of goldenrod (*Solidago*: Compositae). *Ecological Monographs*, 53(1), 95–117.
- Grover, A., Twell, D., & Schleiff, E. (2016). Pollen as a target of environmental changes. *Plant Reproduction*, 29(1), 1–2.
- Gryj, E., del Rio, C. M., & Baker, I. (1990). Avian pollination and nectar use in *Combretum fruticosum* (Loefl.). *Biotropica*, 22(3), 266–271.
- Gutián, J., Gutián, P., & Sánchez, J. M. (1993). Reproductive biology of two *Prunus* species (Rosaceae) in the northwest Iberian Peninsula. *Plant Systematics and Evolution*, 185, 153–165.
- Gupta, M., & Murty, Y. S. (1985). Viability and longevity of pollen in *Vicia faba* L. *Acta Botanica Indica*, 13(1), 85–87.
- Haber, W. A., & Frankie, G. W. (1989). A tropical hawkmoth community: Costa Rican dry forest Sphingidae. *Biotropica*, 21(2), 155–172.
- Hackney, E. E., & McGraw, J. B. (2001). Experimental demonstration of an Allee effect in American ginseng. *Conservation Biology*, 15(1), 129–136.
- Hallmann, C. A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., & De Kroon, H. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLOS ONE*, 12(10), e0185809.
- Hamed, S., & Ghezlaoui, B. (2020). Effect of climatic interference on the phenological stages of the cherry tree *Prunus cerasus* in Tlemcen region, Algeria. *Madras Agricultural Journal*, 107, 395–399.
- Hansen, H. P. (1949). Pollen content of moss polsters in relation to forest composition. *American Midland Naturalist*, 41(2), 473–479.
- Harder, L. D., & Barrett, S. C. (1996). Pollen dispersal and mating patterns in animal-pollinated plants. In *Floral biology: Studies on floral evolution in animal-pollinated plants* (pp. 140–190). Springer US.
- Harder, L. D., & Johnson, S. D. (2008). Function and evolution of aggregated pollen in angiosperms. *International Journal of Plant Sciences*, 169(1), 59–78.

- Harris, L. F., & Johnson, S. D. (2004). The consequences of habitat fragmentation for plant–pollinator mutualisms. *International Journal of Tropical Insect Science*, 24(1), 29-43.
- Harrison, T., & Winfree, R. (2015). Urban drivers of plant-pollinator interactions. *Functional Ecology*, 29, 879–888.
- Hedden, P., & Phillips, A. L. (2000). Manipulation of hormone biosynthetic genes in transgenic plants. *Current Opinion in Biotechnology*, 11(2), 130–137.
- Hedhly, A., Hormaza, J. I., & Herrero, M. (2003). The effect of temperature on stigmatic receptivity in sweet cherry (*Prunus avium* L.). *Plant, Cell & Environment*, 26(10), 1673-1680.
- Hegland, S. J., Nielsen, A., Lázaro, A., Bjerknes, A. L., & Totland, Ø. (2009). How does climate warming affect plant-pollinator interactions?. *Ecology Letters*, 12(2), 184-195.
- Heithaus, E. R., Opler, P. A., & Baker, H. G. (1974). Bat activity and pollination of *Bauhinia pauletia*: Plant-pollinator coevolution. *Ecology*, 55(2), 412–419.
- Helden, A. J., Stamp, G. C., & Leather, S. R. (2012). Urban biodiversity: Comparison of insect assemblages on native and non-native trees. *Urban Ecosystems*, 15, 611–624.
- Hennig, E. I., & Ghazoul, J. (2012). Pollinating animals in the urban environment. *Urban Ecosystems*, 15, 149-166.
- Herrera, C. M. (1987). Components of pollinator "quality": Comparative analysis of a diverse insect assemblage. *Oikos*, 50(1), 79-90.
- Herrera, C. M. (1989). Pollinator abundance, morphology, and flower visitation rate: Analysis of the “quantity” component in a plant-pollinator system. *Oecologia*, 80(2), 241-248.
- Herrera, C. M., Castellanos, M. C., & Medrano, M. (2006). Geographical context of floral evolution: Towards an improved research programme in floral diversification. In L. D. Harder & S. C. H. Barrett (Eds.), *Ecology and Evolution of Flowers* (pp. 278-294). Oxford University Press.
- Herrero, M. (1983). Factors affecting fruit set in 'Agua de Aranjuez' pear. *Acta Horticulturae*, 139, 91–96.

- Heslop-Harrison, J., Heslop-Harrison, Y., & Shivanna, K. R. (1984). The evaluation of pollen quality, and a further appraisal of the fluorochromatic (FCR) test procedure. *Theoretical and Applied Genetics*, 67(4), 367-375.
- Hickman, J. C. (1974). Pollination by ants: A low-energy system. *Science*, 184(4143), 1290–1292.
- Hidalgo, P. J., Galán, C., & Domínguez, E. (1999). Pollen production of the genus *Cupressus*. *Grana*, 38(5), 296–300.
- Holm, S. (1994). Reproductive variability and pollen limitation in three *Betula* taxa in Northern Sweden. *Ecography*, 17, 73-81.
- Hülsmann, M., von Wehrden, H., Klein, A. M., & Leonhardt, S. D. (2015). Plant diversity and composition compensate for negative effects of urbanization on foraging bumble bees. *Apidologie*, 46(6), 760-770.
- Huryn, V. M. B. (1997). Ecological impacts of introduced honey bees. *The Quarterly Review of Biology*, 72(3), 275-297.
- Hyde, H. A. (1952). Studies in atmospheric pollen. V. A daily census of pollen at Cardiff for the six years 1943–48. *New Phytologist*, 51, 281–293.
- Hyde, H. A., & Williams, D. A. (1944). Studies in atmospheric pollen. I. A daily census of pollens at Cardiff, 1942. *The New Phytologist*, 43(1), 49–61.
- Hyde, H. A., & Williams, D. A. (1946). Studies in atmospheric pollen III. Pollen production and pollen incidence in Ribwort plantain (*Plantago lanceolata*). *New Phytologist*, 45(1), 271–277.
- Imani, A., & Nazarian, M. (2013). Effects of boron and growth regulators on germination of *Punica granatum* pollen grains. *Advanced Crop Science*, 3, 268–272.
- Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate change 2014: Synthesis Report*. Geneva, Switzerland.
- Internicola, A. I., & Harder, L. D. (2012). Bumble-bee learning selects for both early and long flowering in food-deceptive plants. *Proceedings of the Royal Society B: Biological Sciences*, 279(1733), 1538-1543.
- IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2016). *The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators*,

- pollination and food production* (S. G. Potts, V. L. Imperatriz-Fonseca, & H. T. Ngo, Eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.
- Ishida, K., & Hiura, T. (1998). Pollen fertility and flowering phenology in an androdioecious tree, *Fraxinus lanuginosa* (Oleaceae), in Hokkaido, Japan. *International Journal of Plant Sciences*, 159(6), 941-947.
- Jabeen, S. S., & Bhat, G. A. (2013). *Impact of air pollution on the performance of hymenopteran pollinators* (Doctoral dissertation).
- Jamshidi, A. R., Imani, A., & Miri, S. M. (2021). Identification of the pollinizer for a new almond genotype 'Karaj 33'. *Journal of Horticulture and Postharvest Research*, 4(4), 521-528.
- Janzen, D. H. (1967). Synchronization of sexual reproduction of trees within the dry season in Central America. *Evolution*, 21(3), 620-637.
- Janzen, D. H., & Hallwachs, W. (2021). To us insectometers, it is clear that insect decline in our Costa Rican tropics is real, so let's be kind to the survivors. *Proceedings of the National Academy of Sciences*, 118(2), e2002546117.
- Jayaprakash, P. (2018). Pollen germination in vitro. In *Pollination in plants* (pp. 81-96). Springer.
- Jayaprakash, P., Sheeba, D., Vikas, V. K., Sivasamy, M., & Sabesan, T. (2018). Development of pollen germination medium to test pollen viability of eggplant and its wild species. *Indian Journal of Horticulture*, 75(2), 237-244.
- Jennersten, O. L. A. (1988). Pollination in *Dianthus deltoides* (Caryophyllaceae): Effects of habitat fragmentation on visitation and seed set. *Conservation Biology*, 2(4), 359-366.
- Jennersten, O. L. A. (1988). Pollination in *Dianthus deltoides* (Caryophyllaceae): Effects of habitat fragmentation on visitation and seed set. *Conservation Biology*, 2(4), 359-366.
- Johnson, S. D., & Govender, K. (2022). Rodent responses to volatile compounds provide insights into the function of floral scent in mammal-pollinated plants. *Philosophical Transactions of the Royal Society B*, 377(1853), 20210167.
- Johnson, S. D., & Steiner, K. E. (2000). Generalization versus specialization in plant pollination systems. *Trends in Ecology & Evolution*, 15(4), 140-143.

- Johnson, S. D., Harder, L. D., & Barrett, S. C. H. (2006). Pollinator-driven speciation in plants. In L. D. Harder & S. C. H. Barrett (Eds.), *Ecology and evolution of flowers* (pp. 295–310). Oxford University Press.
- Johnson, S. D., Pauw, A., & Midgley, J. (2001). Rodent pollination in the African lily *Massonia depressa* (Hyacinthaceae). *American Journal of Botany*, 88(10), 1768-1773.
- Johri, B. M. F., & Vasil, I. K. (1961). Physiology of pollen. *The Botanical Review*, 27, 325-381.
- Jones, D. F. (1928). *Selective fertilization*. University of Chicago Press.
- Joppa, L. R., McNeal, F. H., & Berg, M. A. (1968). Pollen production and pollen shedding of hard red spring (*Triticum aestivum* L. emThell.) and durum (*T. durum* Desf.) wheats. *Crop Science*, 8(4), 487-490.
- Jordano, P. (1993). Pollination biology of *Prunus mahaleb* L.: Deferred consequences of gender variation for fecundity and seed size. *Biological Journal of the Linnean Society*, 50, 65–84.
- Joseph, N., Anjum, N., & Tripathi, Y. C. (2016). Phytochemical screening and evaluation of polyphenols, flavonoids, and antioxidant activity of *Prunus cerasoides* D. Don leaves. *Journal of Pharmacy Research*, 10(7), 502-508.
- Joshi, A. R., Smith, J. L. D., & Cuthbert, F. J. (1995). Influence of food distribution and predation pressure on spacing behavior in palm civets. *Journal of Mammalogy*, 76(4), 1205-1212.
- Jürgens, A., Witt, T., & Gottsberger, G. (2002). Pollen grain numbers, ovule numbers and pollen–ovule ratios in Caryophylloideae: Correlation with breeding system, pollination, life form, style number, and sexual system. *Sexual Plant Reproduction*, 14, 279–289.
- Katara, M. M. (2013). In vitro pollen germination of *Datura metel* L. (5): Effect of hormones. *International Journal of Scientific Research*, 2(12), 51–52.
- Kato, M., & Kawakita, A. (2004). Plant-pollinator interactions in New Caledonia influenced by introduced honey bees. *American Journal of Botany*, 91(11), 1814-1827.

- Katz, D. S., Morris, J. R., & Batterman, S. A. (2020). Pollen production for 13 urban North American tree species: allometric equations for tree trunk diameter and crown area. *Aerobiologia*, 36(3), 401–415.
- Kaur, N., & Kaleka, A. S. (2022). Diversity, importance, and decline of pollinating insects in present era. In *Global decline of insects* (p. 85).
- Kearns, C. A., & Inouye, D. W. (1997). Pollinators, flowering plants, and conservation biology. *BioScience*, 47(5), 297-307.
- Kearns, C. A., Inouye, D. W., & Waser, N. M. (1998). Endangered mutualisms: The conservation of plant-pollinator interactions. *Annual Review of Ecology and Systematics*, 29(1), 83–112.
- Kehimkar, I. D. (2008). *Book of Indian butterflies*. Oxford University Press.
- Kelly, D., & Sork, V. L. (2002). Mast seeding in perennial plants: Why, how, where? *Annual Review of Ecology and Systematics*, 33(1), 427-447.
- Kerr, J. T., Pindar, A., Galpern, P., Packer, L., Potts, S. G., Roberts, S. M., & Pantoja, A. (2015). Climate change impacts on bumblebees converge across continents. *Science*, 349(6244), 177-180.
- Kerr, W. E., Carvalho, G. A., & Nascimento, V. A. (1999). The probable consequences of the destruction of Brazilian stingless bees. *Advances in Economic Botany*, 13, 395-403.
- Kevan, P. G. (1989). Thermoregulation in arctic insects and flowers: Adaptation and co-adaptation in behaviour, anatomy, and physiology. In *Thermal Physiology* (pp. 747-753). Elsevier Science Publishers B.V. (Biomedical Division).
- Kevan, P. G. (1999). Pollinators as bioindicators of the state of the environment: Species, activity, and diversity. In *Invertebrate biodiversity as Bioindicators of Sustainable Landscapes* (pp. 373-393). Elsevier.
- Kevan, P. G., & Baker, H. G. (1983). Insects as flower visitors and pollinators. *Annual Review of Entomology*, 28(1), 407–453.
- Khalifman, I. (1951). *Bee*. Foreign Language Publishing House, Moscow.
- Khan, M. A., Mahmood, I. A., & Aslam, M. (1999). Effect of hormones and antibiotics on pollen grain germination. *International Journal of Agriculture and Biology*, 1, 215–217.

- Khanduri, V. P. (2011). Anthesis and anther dehiscence in some tropical tree species of Mizoram, India. *Life Sciences Leaflets*, 19, 793–803.
- Khanduri, V. P. (2012a). Annual variation in floral phenology and pollen production in a 25-year-old plantation of *Tectona grandis*. *Nordic Journal of Botany*, 30(1), 82–89.
- Khanduri, V. P. (2012b). Temporal and spatial variation of pollen yield in natural populations of *Pinus roxburghii*. *Forestry Studies in China*, 14(1), 20–29.
- Khanduri, V. P. (2014). Annual variation in floral phenology and pollen production in *Lagerstroemia speciosa*: An entomophilous tropical tree. *Songklanakarin Journal of Science & Technology*, 36(4), 389–396.
- Khanduri, V. P., & Sharma, C. M. (2000). Development of groups of male strobili, anthesis and microsporangium dehiscence in *Pinus roxburghii*. *Grana*, 39(4), 169–174.
- Khanduri, V. P., & Sharma, C. M. (2002a). Pollen production, microsporangium dehiscence and pollen flow in Himalayan cedar (*Cedrus deodara* Roxb. ex D. Don). *Annals of Botany*, 89(5), 587–593.
- Khanduri, V. P., & Sharma, C. M. (2002b). Pollen productivity variations, pollen-ovule ratio and sexual selection in *Pinus roxburghii*. *Grana*, 41(1), 29–38.
- Khanduri, V. P., Kumar, K. S., & Sharma, C. M. (2015b). Role of pollen production in mating success in some tropical tree species. *Brazilian Journal of Botany*, 38(1), 107–112.
- Khanduri, V. P., Kumar, K. S., Sharma, C. M., Riyal, M. K., Kar, K., Singh, B., & Sukumaran, A. (2021). Passerine birds supporting cross pollination in *Erythrina stricta* Roxb. *Dendrobiology*, 85.
- Khanduri, V. P., Sharma, C. M., Kumar, K. S., & Kar, K. (2015a). Biannual pollen production in *Lagerstroemia speciosa* (L.) Pers. (Lythraceae). *Grana*, 54(1), 26–36.
- Khanduri, V. P., Sharma, C. M., Kumar, K. S., & Ghildiyal, S. K. (2013). Annual variation in flowering phenology, pollination, mating system, and pollen yield in two natural populations of *Schima wallichii* (DC.) Korth. *The Scientific World Journal*, 2013(1), 350157.

- Khanduri, V. P., Sukumaran, A., & Sharma, C. M. (2019). Reproductive biology of *Cornus capitata* Wall. ex Roxb.: A native species in East Asia. *Journal of Forestry Research*, 30(6), 2039–2050.
- Khurana, D. K., & Khosla, P. K. (1979). Pollen viability and germination studies in some hardwood species. *Indian Journal of Forestry*, 2, 191-192.
- Kim, S. K., Lagerstedt, H. B., & Daley, L. S. (1985). Germination responses of filbert pollen to pH, temperature, glucose, fructose, and sucrose. *HortScience*, 15(1), 81–82.
- King, J. R. (1960). The peroxidase reaction as an indicator of pollen viability. *Stain Technology*, 35(4), 225–227.
- Kingston, A. B., & McQuillan, P. B. (2000). Are pollination syndromes useful predictors of floral visitors in Tasmania? *Austral Ecology*, 25(6), 600-609.
- Kitching, R. L., Boulter, S. L., Howlett, B. G., & Goodall, K. (2007). Visitor assemblages at flowers in a tropical rainforest canopy. *Austral Ecology*, 32(1), 29-42.
- Klein, A. M., Steffan-Dewenter, I., & Tscharntke, T. (2003). Fruit set of highland coffee increases with the diversity of pollinating bees. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 270(1518), 955–961.
- Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, 274(1608), 303–313.
- Kleizen, C., Midgley, J., & Johnson, S. D. (2008). Pollination systems of *Colchicum* (Colchicaceae) in Southern Africa: Evidence for rodent pollination. *Annals of Botany*, 102(5), 747-755.
- Klomberg, Y., Tropek, R., Mertens, J. E. J., Kobe, I. N., Hodeček, J., Raška, J., Fominka, N. T., Souto-Vilarós, D., Janečková, P., & Janeček, Š. (2022). Spatiotemporal variation in the role of floral traits in shaping tropical plant–pollinator interactions. *Ecology Letters*, 25(4), 839–850.
- Koubouris, G. C., Metzidakis, I. T., & Vasilakakis, M. D. (2012). Intraspecific variation in pollen viability, germination, and ultrastructure of *Olea europaea* L. *African Journal of Biotechnology*, 11(70), 13442-13446.

- Kour, G. (2018). Studies on floral morphology of subtropical plum (*Prunus salicina* Lindl.). *International Journal of Current Microbiology and Applied Sciences*, 7(8), 801–811.
- Kremen, C., Williams, N. M., & Thorp, R. W. (2002). Crop pollination from native bees at risk from agricultural intensification. *Proceedings of the National Academy of Sciences*, 99(26), 16812–16816.
- Kremen, C., Williams, N. M., Aizen, M. A., Gemmill-Herren, B., LeBuhn, G., Minckley, R., & Ricketts, T. H. (2007). Pollination and other ecosystem services produced by mobile organisms: A conceptual framework for the effects of land-use change. *Ecology Letters*, 10(4), 299–314.
- Kudo, G., & Harder, L. D. (2005). Floral and inflorescence effects on variation in pollen removal and seed production among six legume species. *Functional Ecology*, 19, 245–254.
- Kulloli, S. K., & Sreekala, A. K. (2009). Pollination ecology of *Rauvolfia micrantha* Hook. F. (Apocynaceae): A critically endangered medicinal plant from the southern Western Ghats. *Phytomorphology*, 59(3/4), 96–101.
- Kulloli, S. K., Chandore, A. N., & Aitawade, M. M. (2011). Nectar dynamics and pollination studies in three species of *Lamiaceae*. *Current Science*, 509–516.
- Kumar, A. V., Prasad, S. V., & Rao, G. R. (1981). Influence of growth regulators on germination of pollen of three tree species. *Department of Botany, S.V. University, Tirupati, India*.
- Kumar, K. S., & Khanduri, V. P. (2016). Flower pollinator interactions within two tropical tree species of Mizoram, North East India. *Notulae Scientia Biologicae*, 8(2), 256–262.
- Kunin, W. E. (1993). Sex and the single mustard: Population density and pollinator behavior effects on seed-set. *Ecology*, 74(7), 2145–2160.
- Kurniawan, V., Putri, D. M., Normasiwi, S., & Surya, M. I. (2021). Phenology and morphological flower of *Prunus cerasoides* Buch.-Ham. ex D. Don. In *IOP Conference Series: Earth and Environmental Science* (Vol. 948, No. 1, p. 012047). IOP Publishing.
- Kwak, M. M., & Bekker, R. M. (2006). Ecology of plant reproduction: Extinction risks and restoration perspectives of rare plant species. In N. M. Waser & J.

- Ollerton (Eds.), *Plant-Pollinator Interactions: From Specialization to Generalization* (pp. 362-386). University of Chicago Press.
- Kyogoku, D. (2015). Reproductive interference: Ecological and evolutionary consequences of interspecific promiscuity. *Population Ecology*, 57, 253-260.
- LaDeau, S. L., & Clark, J. S. (2006). Pollen production by *Pinus taeda* growing in elevated atmospheric CO₂. *Functional Ecology*, 20(3), 541-547.
- Laithwaite, E., Watson, A., Whalley, P. E. S., & Duckworth, W. D. (1975). *The dictionary of butterflies and moths in colour* (pp. 1–xlvi, 147–296, 405 col. figs.).
- Laldinpuii, H., & Mishra, B. P. (2019). Assessment of the chemical characteristics of river Serlui-A in Aizawl, Mizoram, North East, India. *Environment and Ecology*, 37(4), 1141–1146.
- Lang, W., Chen, X., Liang, L., Ren, S., & Qian, S. (2019). Geographic and climatic attributions of autumn land surface phenology spatial patterns in the temperate deciduous broadleaf forest of China. *Remote Sensing*, 11(13), 1546.
- Larson, B. M., & Barrett, S. C. (2000). A comparative analysis of pollen limitation in flowering plants. *Biological Journal of the Linnean Society*, 69(4), 503-520.
- Leduc, N., Monnier, M., & Douglas, G. C. (1990). Germination of trinucleated pollen: Formulation of a new medium for *Capsella bursa-pastoris*. *Sexual Plant Reproduction*, 3, 228–235.
- Lee, S. L., Ng, K. K., Saw, L. G., Lee, C. T., Muhammad, N., Tani, N., and Koskela, J. (2006). Linking the gaps between conservation research and conservation management of rare dipterocarps: a case study of *Shorea lumutensis*. *Biological Conservation*, 131(1), 72-92.
- Lemaitre, A. B., Pinto, C. F., & Niemeyer, H. M. (2014). Generalized pollination system: Are floral traits adapted to different pollinators? *Arthropod-Plant Interactions*, 8, 261-272.
- Levin, D. A., & Anderson, W. W. (1970). Competition for pollinators between simultaneously flowering species. *The American Naturalist*, 104(939), 455-467.

- Levin, D. A., Kerster, H. W., & Niedzlek, M. (1971). Pollinator flight directionality and its effect on pollen flow. *Evolution*, 25(1), 113–118.
- Linhart, Y. B., Busby, W. H., Beach, J. H., & Feinsinger, P. (1987). Forager behavior, pollen dispersal, and inbreeding in two species of hummingbird-pollinated plants. *Evolution*, 41(3), 679–682.
- Lloyd, D. G. (1982). Selection of combined versus separate sexes in seed plants. *The American Naturalist*, 120(5), 571–585.
- Lloyd, D. G., & Schoen, D. J. (1992). Self- and cross-fertilization in plants. I. Functional dimensions. *International Journal of Plant Sciences*, 153(3, Part 1), 358–369.
- Løken, A. (1981). Flower-visiting insects and their importance as pollinators. *Bee World*, 62(4), 130–140.
- Lopez, J., Devesa, J. A., Ortega-Olivencia, A., & Ruiz, T. (2000). Production and morphology of fruit and seeds in *Genisteae* (Fabaceae) of south-west Spain. *Botanical Journal of the Linnean Society*, 132, 97–120.
- Lundgren, M. R., & Des Marais, D. L. (2020). Life history variation as a model for understanding trade-offs in plant–environment interactions. *Current Biology*, 30(4), R180–R189.
- Majid, S., Kumar, A., Naseer, S., Bashir, S., Mughal, M. N., Dar, Z. A., Amin, A., Rashid, Z., Rasool, F., & Haqem, S. (2021). Floral biology of exotic and indigenous almond (*Prunus amygdalus* Batsch.) genotypes under temperate conditions of Kashmir valley. *International Journal of Current Microbiology and Applied Sciences*, 10(01), 2807–2813.
- Marshall, A. G. (1983). Bats, flowers and fruit: Evolutionary relationships in the Old World. *Biological Journal of the Linnean Society*, 20(1), 115–135.
- Marshall, D. L., & Ellstrand, N. C. (1986). Sexual selection in *Raphanus sativus*: Experimental data on nonrandom fertilization, maternal choice, and consequences of multiple paternity. *The American Naturalist*, 127(4), 446–461.
- Martén, S., & Quesada, M. (2001). Phenology, sexual expression, and reproductive success of the rare neotropical palm *Geonomea petiolata*. *Biotropica*, 33(4), 596–605.

- Martínez-Gómez, P., Sozzi, G. O., Sánchez-Pérez, R., Rubio, M., & Gradziel, T. M. (2003). New approaches to *Prunus* tree crop breeding. *Journal of Food Agriculture and Environment*, 1, 52-63.
- Martínez-Peralta, C., Gonzaga-Segura, J. A., & Arroyo-Cosultchi, G. (2022). Floral biology of two woody species of *Dalbergia* at high risk of timber extraction. *Brazilian Journal of Botany*, 45(2), 743–753.
- Martins, K. T., Gonzalez, A., & Lechowicz, M. J. (2015). Pollination services are mediated by bee functional diversity and landscape context. *Agriculture, Ecosystems & Environment*, 200, 12–20.
- MataniBorkheyli, M., Miri, S. M., & Nabigol, A. (2021). In vitro multiplication and rooting of GF677 rootstock. *Journal of Horticulture and Postharvest Research*, 4(2), 243-252.
- Mateos-Fierro, Z., Garratt, M. P., Fountain, M. T., Ashbrook, K., & Westbury, D. B. (2022). Wild bees are less abundant but show better pollination behaviour for sweet cherry than managed pollinators. *Journal of Applied Entomology*, 146(4), 361-371.
- Mathur, G., & Ram, H. M. (1978). Significance of Petal Colour in Thrips-pollinated *Lantana camara* L. *Annals of Botany*, 42(182), 1473-1476.
- Matteson, K. C., & Langellotto, G. A. (2010). Determinants of inner city butterfly and bee species richness. *Urban Ecosystems*, 13(3), 333–347.
- Matteson, K. C., & Langellotto, G. A. (2011). Small-scale additions of native plants fail to increase beneficial insect richness in urban gardens. *Insect Conservation and Diversity*, 4(1), 89–98.
- Mayfield, M. M. (2005). The importance of nearby forest to known and potential pollinators of oil palm (*Elaeis guineensis* Jacq.; Arecaceae) in southern Costa Rica. *Economic Botany*, 59(2), 190-196.
- Mayfield, M. M., Waser, N. M., & Price, M. V. (2001). Exploring the ‘most effective pollinator principle’ with complex flowers: Bumblebees and *Ipomopsis aggregata*. *Annals of Botany*, 88(4), 591-596.
- McCallum, K. P., McDougall, F. O., & Seymour, R. S. (2013). A review of the energetics of pollination biology. *Journal of Comparative Physiology B*, 183, 867-876.

- McConchie, C. A., & Knox, R. B. (1989). Pollination and reproductive biology of seagrasses. In *Biology of Seagrasses: A Treatise on the Biology of Seagrasses with Special Reference to the Australian Region* (pp. 74-111).
- McLaughlin, R., Keller, J., Wagner, E., Biddinger, D., Grozinger, C., & Hoover, K. (2022). Insect visitors of black cherry (*Prunus serotina*) (Rosales: Rosaceae) and factors affecting viable seed production. *Environmental Entomology*, 51(2), 471–481.
- Medan, D., Zarlavsky, G., & Bartoloni, N. J. (2013). Plant reproduction in the high-Andean puna: *Kentrothamnus weddellianus* (Rhamnaceae: Colletieae). *Plant Systematics and Evolution*, 299(5), 841–851.
- Memmott, J., Waser, N. M., & Price, M. V. (2004). Tolerance of pollination networks to species extinctions. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 271(1557), 2605-2611.
- Mercuri, A. M., Torri, P., Fornaciari, R., & Florenzano, A. (2016). Plant responses to climate change: the case study of Betulaceae and Poaceae pollen seasons (Northern Italy, Vignola, Emilia-Romagna). *Plants*, 5(4), 42.
- Michener, C. D. (2007). *The bees of the world*. Johns Hopkins University Press.
- Millard, J., Outhwaite, C. L., Kinnersley, R., Freeman, R., Gregory, R. D., Adedjoja, O., & Newbold, T. (2021). Global effects of land-use intensity on local pollinator biodiversity. *Nature Communications*, 12(1), 2902.
- Miller-Rushing, A. J., & Inouye, D. W. (2009). Variation in the impact of climate change on flowering phenology and abundance: an examination of two pairs of closely related wildflower species. *American Journal of Botany*, 96(10), 1821-1829.
- Milutinović, M., Nikolić, D., Fotirić, M., & Janković, D. (2006). In vitro pollen germination of peach cultivars. In *XXVII International Horticultural Congress-IHC2006: II International Symposium on Plant Genetic Resources of Horticultural 760* (pp. 451-456).
- Mione, T., & Anderson, G. J. (1992). Pollen-ovule ratios and breeding system evolution in *Solanum* section *Basarthrum* (Solanaceae). *American Journal of Botany*, 79, 279–287.

- Mir, S. A. D. G., Parry, M., Yaqob, M., & Nisar, M. (2017). Threats of anthropogenic pressure on insect pollinators. *Vegetos*, 30(2), 469–476.
- Mitchell, R. J., Irwin, R. E., Flanagan, R. J., & Karron, J. D. (2009). Ecology and evolution of plant–pollinator interactions. *Annals of Botany*, 103(9), 1355–1363.
- Molano-Flores, B., & Cohen, J. I. (2024). Introduction to the Special Issue of Plants on “Advances in Plant Reproductive Ecology and Conservation Biology”. *Plants*, 13(5), 605.
- Molina, R. T., Rodríguez, A. M., Palaciso, I. S., & López, F. G. (1996). Pollen production in anemophilous trees. *Grana*, 35(1), 38–46.
- Momose, K., Yumoto, T., Nagamitsu, T., Kato, M., Nagamasu, H., Sakai, S., & Inoue, T. (1998). Pollination biology in a lowland dipterocarp forest in Sarawak, Malaysia. I. Characteristics of the plant-pollinator community in a lowland dipterocarp forest. *American Journal of Botany*, 85(10), 1477–1501.
- Mondal, S., & Ghanta, R. (2012). Studies on in vitro pollen germination of *Lawsonia inermis* Linn. *Advances in Bio research*, 3(3), 63–66.
- Mondal, S., & Mandal, S. (1999). Entomophilous pollen incidence with reference to atmospheric dispersal in eastern India. *Aerobiologia*, 15(4), 311–315.
- Montalvo, A. M. (1992). Relative success of self and outcross pollen comparing mixed-and single-donor pollinations in *Aquilegia caerulea*. *Evolution*, 46(4), 1181–1198.
- Montoya-Pfeiffer, P. M., Rodrigues, R. R., & Alves dos Santos, I. (2020). Bee pollinator functional responses and functional effects in restored tropical forests. *Ecological Applications*, 30(3), e02054.
- Moore, P. D., Webb, J. A., & Collinson, M. E. (1991). *Pollen analysis* (2nd ed.). Blackwell Scientific Publications. pp. 42–46 & 181–182.
- Morales, C. L., & Traveset, A. (2008). Interspecific pollen transfer: magnitude, prevalence and consequences for plant fitness. *Critical Reviews in Plant Sciences*, 27(4), 221–238.
- Morellato, L. P. C., Camargo, M. G. G., D’Eça Neves, F. F., Luize, B. G., Mantovani, A., & Hudson, I. L. (2010). The influence of sampling method, sample size, and frequency of observations on plant phenological patterns and

- interpretation in tropical forest trees. In *Springer Netherlands* (pp. 99-121). Springer.
- Muchhala, N. (2003). Exploring the boundary between pollination syndromes: Bats and hummingbirds as pollinators of *Burmeistera cyclostigmata* and *B. tenuiflora* (Campanulaceae). *Oecologia*, 134(3), 373-380.
- Munguía-Rosas, M. A., Ollerton, J., & Parra-Tabla, V. (2011a). Phenotypic selection on flowering phenology and size in two dioecious plant species with different pollen vectors. *Plant Species Biology*, 26(3), 205-212.
- Munguía-Rosas, M. A., Ollerton, J., Parra-Tabla, V., & De-Nova, J. A. (2011b). Meta-analysis of phenotypic selection on flowering phenology suggests that early flowering plants are favoured. *Ecology Letters*, 14(5), 511-521.
- Munson, S. M., & Long, A. L. (2017). Climate drives shifts in grass reproductive phenology across the western USA. *New Phytologist*, 213(4), 1945–1955.
- Nabhan, G. P., & Buchmann, S. L. (1997). Services provided by pollinators. In G. C. Daily (Ed.), *Nature's services: Societal dependence on natural ecosystems* (pp. 133–150). Island Press.
- Nagaar, B. (2017). *Reproductive biology of Bauhinia vahlii Wight & Arn.* (Doctoral dissertation, Dr. YS Parmar University of Horticulture and Forestry, Nauni).
- Nair, P. K. K., & Rastogi, K. (1963). Pollen production in some allergenic plants. *Current Science*, 32(12), 566.
- Nascimento, V. T., Agostini, K., Souza, C. S., & Maruyama, P. K. (2020). Tropical urban areas support highly diverse plant-pollinator interactions: An assessment from Brazil. *Landscape and Urban Planning*, 198, 103801.
- Nasrallah, J. B., & Nasrallah, M. E. (2014). S-locus receptor kinase signalling. *Biochemical Society Transactions*, 42(2), 313-319.
- Ne'eman, G., Jürgens, A., Newstrom-Lloyd, L., Potts, S. G., & Dafni, A. (2010). A framework for comparing pollinator performance: effectiveness and efficiency. *Biological Reviews*, 85(3), 435-451.
- Nemhauser, J. L., Feldman, L. J., & Zambryski, P. C. (2000). Auxin and ETTIN in *Arabidopsis* gynoecium morphogenesis. *Development*, 127(18), 3877-3888.
- Nepal, S., Trunschke, J., Ren, Z. X., Burgess, K. S., & Wang, H. (2023). Community-wide patterns in pollen and ovule production, their ratio (P/O), and other floral

- traits along an elevation gradient in southwestern China. *BMC Plant Biology*, 23(1), 425.
- Nepi, M., Soligo, C., Nocentini, D., Abate, M., Guarnieri, M., Cai, G., & Pacini, E. (2012). Amino acids and protein profile in floral nectar: much more than a simple reward. *Flora - Morphology, Distribution, Functional Ecology of Plants*, 207(7), 475-481.
- Neto, H. F. P. (2013). Floral biology and breeding system of *Bauhinia forficata* (Leguminosae: Caesalpinioideae), a moth-pollinated tree in southeastern Brazil. *Brazilian Journal of Botany*, 36(1), 55–64.
- Newstrom, L. E., Frankie, G. W., & Baker, H. G. (1994). A new classification for plant phenology based on flowering patterns in lowland tropical rain forest trees at La Selva, Costa Rica. *Biotropica*, 26(2), 141-159.
- Nicholls, E., Ely, A., Birkin, L., Basu, P., & Goulson, D. (2020). The contribution of small-scale food production in urban areas to the sustainable development goals: A review and case study. *Sustainability Science*, 15, 1585–1599.
- Nikolić, D., Rakonjac, V., & Fotirić-Akšić, M. (2012). The effect of pollenizer on the fruit set of plum cultivar Čačanska Najbolja. *Journal of Agricultural Sciences (Belgrade)*, 57(1), 9-18.
- Nilsson, L. A., Johnsson, L., Ralison, L., & Randrianjohany, E. (1987). Angraecoid orchids and hawkmoths in central Madagascar: specialized pollination systems and generalist foragers. *Biotropica*, 19(4), 310-318.
- Normasiwi, S. (2015). Flowering period of three species of *Prunus* collection in Cibodas Botanic Garden. *Widyariset*, 1(1), 71–78.
- Normasiwi, S., Hafizhah, S. S., & Surya, M. I. (2024). A preliminary study of pollination *Prunus* sp. in Cibodas Botanic Gardens. In *AIP Conference Proceedings* (Vol. 3165, No. 1). AIP Publishing.
- Normasiwi, S., Hafizhah, S. S., Adviany, I., & Surya, M. I. (2023). Evaluation of reproduction biology of *Prunus cerasoides*. *Notulae Scientia Biologicae*, 15(3), 11601.
- Nussbaumer, A., Waldner, P., Apuhtin, V., Aytar, F., Benham, S., Bussotti, F., & Gessler, A. (2018). Impact of weather cues and resource dynamics on mast

- occurrence in the main forest tree species in Europe. *Forest Ecology and Management*, 429, 336-350.
- Oberle, G. D., & Watson, R. (1953). The use of 2,3,5-triphenyl tetrazolium chloride in viability tests of fruit pollens. *Proceedings of the American Society for Horticultural Science*, 61, 299–303.
- Octavia, G. A. E., Iryadi, R., Warseno, T., & Purnobasuki, H. (2023). Short communication: The flowering process of *Prunus cerasoides* in Bali Botanic Gardens, Indonesia. *Biodiversitas*, 24(2), 1186–1191.
- Oldland, B., Kelley, D., Tomon, T., Larcenaire, C., Turcotte, R., & Saf, J. (2019). Black cherry pollinator augmentation, Spring 2019 and 2021.
- Olesen, J. M., & Valido, A. (2003). Lizards as pollinators and seed dispersers: An island phenomenon. *Trends in Ecology & Evolution*, 18(4), 177-181.
- Oliveira, W., e Silva, J. L. S., de Oliveira, M. T. P., Cruz-Neto, O., da Silva, L. A. P., Borges, L. A., & Lopes, A. V. (2019). Reduced reproductive success of the endangered tree brazilwood (*Paubrasilia echinata*, Leguminosae) in urban ecosystem compared to Atlantic forest remnant: Lessons for tropical urban ecology. *Urban Forestry & Urban Greening*, 41, 303–312.
- Ollerton, J. (2017). Pollinator diversity: Distribution, ecological function, and conservation. *Annual Review of Ecology, Evolution, and Systematics*, 48, 353–376.
- Ollerton, J., Winfree, R., & Tarrant, S. (2011). How many flowering plants are pollinated by animals? *Oikos*, 120(3), 321-326.
- Olsen, K. M. (1996). Pollination effectiveness and pollinator importance in a population of *Heterotheca subaxillaris* (Asteraceae). *Oecologia*, 109(1), 114-121.
- Opler, P. A., Frankie, G. W., & Baker, H. G. (1980). Comparative phenological studies of treelet and shrub species in tropical wet and dry forests in the lowlands of Costa Rica. *The Journal of Ecology*, 167-188
- Orlandi, F., Aguilera, F., Galan, C., Msallem, M., & Fornaciari, M. J. E. A. (2017). Olive yields forecasts and oil price trends in Mediterranean areas: A comprehensive analysis of the last two decades. *Experimental Agriculture*, 53(1), 71-83.

- Ornduff, R. (1975). Pollen flow in *Lythrum junceum*, a tristylous species. *New Phytologist*, 75(1), 161–166.
- Oteros, J., Orlandi, F., García-Mozo, H., Aguilera, F., Dhiab, A. B., Bonofiglio, T., & Galán, C. (2014). Better prediction of Mediterranean olive production using pollen-based models. *Agronomy for Sustainable Development*, 34, 685–694.
- Ottaviano, E., & Mulcahy, D. L. (1989). Genetics of angiosperm pollen. *Advances in Genetics*, 26, 1–64.
- Pachau, R. (1994). Physical geography of Mizoram: Climate. In *Geography of Mizoram* (pp. 41–54). R.T. Enterprise.
- Pacini, E. (1996). Types and meaning of pollen carbohydrate reserves. *Sexual Plant Reproduction*, 9, 362–366.
- Pakkad, G., James, C., Torre, F., Elliott, S., & Blakesley, D. (2004). Genetic variation of *Prunus cerasoides* D. Don, a framework tree species in northern Thailand. *New Forests*, 27, 189–200.
- Pandey, A., Nayar, E. R., Venkateswaran, K., & Bhandari, D. C. (2008). Genetic resources of *Prunus* (Rosaceae) in India. *Genetic Resources and Crop Evolution*, 55(1), 91–104.
- Pannure, A. (2016). Bee pollinators decline: Perspectives from India. *International Research Journal of Natural and Applied Sciences*, 3(5), 2349–4077.
- Parachnowitsch, A. L., & Kessler, A. (2010). Pollinators exert natural selection on flower size and floral display in *Penstemon digitalis*. *New Phytologist*, 188(2), 393–402.
- Parashuram, M., Pavan Kumar, P., Gunnaiah, R., Patil, B. P., Jhalegar, M. J., & Meti, S. (2021). Assessment of pollen viability and in vitro pollen germination in *Nerium* cultivars (*Nerium oleander* L.). *International Journal of Current Science (IJCS)*, 9(2), 724–728.
- Pardee, G. L., & Philpott, S. M. (2014). Native plants are the bee's knees: Local and landscape predictors of bee richness and abundance in backyard gardens. *Urban Ecosystems*, 17(3), 641–659.
- Parfitt, D. E., & Ganeshan, S. (1989). Comparison of procedures for estimating viability of *Prunus* pollen. *HortScience*, 24(2), 354–356.

- Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J. K., Thomas, C. D., Descimon, H., & Warren, M. (1999). Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature*, 399(6736), 579-583.
- Patel, R. G., & Mankad, A. U. (2014). In vitro pollen germination—A review. *International Journal of Science and Research*, 3(5), 304-307.
- Paton, D. C., & Ford, H. A. (1977). Pollination by birds of native plants in South Australia. *Emu - Austral Ornithology*, 77(2), 73–85.
- Paul, S., Dholakia, B. B., & Datta, B. K. (2024). Reproductive biology and pollination ecology of *Ipomoea triloba* L. (Convolvulaceae): An alien invasive species of the Indo-Burma biodiversity hotspot. *Plant Species Biology*, 39(2), 61–76.
- Pearson, H. M., & Harney, P. M. (1984). Pollen viability in *Rosa*. *HortScience*, 19(5), 710–711.
- Pellissier, V., Muratet, A., Verfaillie, F., & Machon, N. (2012). Pollination success of *Lotus corniculatus* (L.) in an urban context. *Acta Oecologica*, 39, 94–100.
- Percival, M. S. (1965). *Floral biology*. Pergamon Press.
- Percival, M. S. (1974). Floral ecology of coastal scrub in southeast Jamaica. *Biotropica*, 6(3), 104–129.
- Pfahler, P. L. (1967). Fertilization ability of maize pollen grains. II. Pollen genotype, female sporophyte and pollen storage interactions. *Genetics*, 57(3), 513–527.
- Pharis, R. P., & King, R. W. (1985). Gibberellins and reproductive development in seed plants. *Annual Review of Plant Physiology*, 36(1), 517–568.
- Pinny, K., & Polito, V. S. (1990). Olive pollen storage and in vitro germination. *Acta Horticulturae*, 286, 207–210.
- Pletsers, A., Caffarra, A., Kelleher, C. T., & Donnelly, A. (2015). Chilling temperature and photoperiod influence the timing of bud burst in juvenile *Betula pubescens* Ehrh. and *Populus tremula* L. trees. *Annals of Forest Science*, 72(6), 941–953.
- Pohl, F. (1937a). *Die Pollenerzeugung der Windblüter: eine vergleichende Untersuchung mit Ausblicken auf den Bestäubungshaushalt tierblütiger Gewächse und die pollenanalytische Waldgeschichtsforschung: (Untersuchungen zur Morphologie und Biologie des Pollens VI)*. C. Heinrich.

- Pohl, F. (1937b). Die Pollen korngewichte einiger windblütiger Pflanzen und ihre ökologische Bedeutung (Beiträge zur Morphologie und Biologie des Pollens VII.). *Botanisches Centralblatt, Beihefte des Botanischen Centralblattes, BBC, Abteilung A, Morphologie und Physiologie der Pflanzen*, 57.
- Polito, V. S., & Luza, J. G. (1988). Longevity of pistachio pollen determined by *in vitro* germination. *Journal of the American Society for Horticultural Science*, 113(2), 214-217.
- Polunin, O., & Stainton, A. (1984). *Flowers of the Himalaya*. Oxford University Press.
- Potter, L. D., & Rowley, J. (1960). Pollen rain and vegetation, San Augustin Plains, New Mexico. *Botanical Gazette*, 122(1), 1-25.
- Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., & Kunin, W. E. (2010). Global pollinator declines: Trends, impacts and drivers. *Trends in Ecology & Evolution*, 25(6), 345–353.
- Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Aizen, M. A., Biesmeijer, J. C., Breeze, T. D., & Vanbergen, A. J. (2016). Safeguarding pollinators and their values to human well-being. *Nature*, 540(7632), 220–229.
- Powney, G. D., Carvell, C., Edwards, M., Morris, R. K., Roy, H. E., Woodcock, B. A., & Isaac, N. J. (2019). Widespread losses of pollinating insects in Britain. *Nature Communications*, 10(1), 1-6.
- Preston, R. E. (1986). Pollen-ovule ratios in the Cruciferae. *American Journal of Botany*, 73, 1732–1740.
- Primack, R. B. (1980). Variation in the phenology of natural populations of montane shrubs in New Zealand. *Journal of Ecology*, 68(3), 849–862.
- Primack, R. B. (1985). Longevity of individual flowers. *Annual Review of Ecology and Systematics*, 16, 15-37.
- Primack, R. B., Duke, N. C., & Tomlinson, P. B. (1981). Floral morphology in relation to pollination ecology in five Queensland coastal plants. *Austrobaileya*, 1, 346–355.
- Proctor, M., Yeo, P., & Lack, A. (1996). *The natural history of pollination* (pp. 479). HarperCollins Publishers.
- Pullaiah, T. (2006). *Encyclopaedia of world medicinal plants* (Vol. 2). Daya books.

- Pyke, G. H. (1991). What does it cost a plant to produce floral nectar? *Nature*, 350(6313), 58-59.
- Rader, R., Bartomeus, I., Garibaldi, L. A., Garratt, M. P., Howlett, B. G., Winfree, R., & Woyciechowski, M. (2016). Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences*, 113(1), 146-151.
- Radičević, S., Nikolić, D., Cerović, R., & Đorđević, M. (2013). In vitro pollen germination and pollen grain morphology in some sweet cherry (*Prunus avium* L.) cultivars. *Romanian Biotechnological Letters*, 18(3), 8341-8349.
- Raju, A. J. S., Rao, S. P., & Rangaiah, K. (2005). Pollination by bats and birds in the obligate outcrosser *Bombax ceiba* L. (Bombacaceae), a tropical dry season flowering tree species in the Eastern Ghats forests of India. *Ornithological Science*, 4(1), 81–87.
- Ramos-Jiliberto, R., Albornoz, A. A., Valdovinos, F. S., Smith-Ramírez, C., Arim, M., Armesto, J. J., & Marquet, P. A. (2009). A network analysis of plant–pollinator interactions in temperate rain forests of Chiloé Island, Chile. *Oecologia*, 160(4), 697–706.
- Rathcke, B. (1983). Competition and facilitation among plants for pollination. In L. Real (Ed.), *Pollination biology* (pp. 305–329). Academic Press.
- Rathcke, B. J. (2000). Hurricane causes resource and pollination limitation of fruit set in a bird-pollinated shrub. *Ecology*, 81(7), 1951-1958.
- Rathcke, B., & Lacey, E. P. (1985). Phenological patterns of terrestrial plants. *Annual Review of Ecology and Systematics*, 16(1), 179–214.
- Ratto, F., Simmons, B. I., Spake, R., Zamora-Gutierrez, V., MacDonald, M. A., Merriman, J. C., & Dicks, L. V. (2018). Global importance of vertebrate pollinators for plant reproductive success: a meta-analysis. *Frontiers in Ecology and the Environment*, 16(2), 82-90.
- Real, L. A., Ott, J., & Silverfine, E. (1982). On the trade-off between mean and variance in foraging: An experimental analysis with bumblebees. *Ecology*, 63(6), 1617–1623.
- Rech, A. R., Dalsgaard, B., Sandel, B., Sonne, J., Svenning, J. C., Holmes, N., & Ollerton, J. (2016). The macroecology of animal versus wind pollination:

- ecological factors are more important than historical climate stability. *Plant Ecology & Diversity*, 9(3), 253-262.
- Reddi, C. S., & Reddi, N. S. (1986). Pollen production in some anemophilous angiosperms. *Grana*, 25(1), 55–61.
- Regal, P. J. (1982). Pollination by wind and animals: ecology of geographic patterns. *Annual Review of Ecology and Systematics*, 13(1), 497-524.
- Regan, E. C., Santini, L., Ingwall-King, L., Hoffmann, M., Rondinini, C., Symes, A., & Butchart, S. H. (2015). Global trends in the status of bird and mammal pollinators. *Conservation Letters*, 8(6), 397–403.
- Réquilé, S., Mazian, B., Grégoire, M., Musio, S., Gautreau, M., Nuez, L., & Ouagne, P. (2021). Exploring the dew retting feasibility of hemp in very contrasting European environments: Influence on the tensile mechanical properties of fibres and composites. *Industrial Crops and Products*, 164, 113337.
- Rhodes, L., Pollard, R. P., & Maxted, N. (2016). *Cerasus cerasoides*. The IUCN Red List of Threatened Species 2016: e.T50026860A50670270.
- Roberts, T. J. (1992). *The birds of Pakistan* (Vol. 2). Oxford University Press.
- Robertson, C. (1895). The philosophy of flower seasons, and the phaenological relations of the entomophilous flora and the anthophilous insect fauna. *The American Naturalist*, 29(338), 97-117.
- Rocha, O. J., & Aguilar, G. (2001). Reproductive biology of the dry forest tree *Enterolobiumcyclocarpum* (Guanacaste) in Costa Rica: A comparison between trees left in pastures and trees in continuous forest. *American Journal of Botany*, 88(9), 1607-1614.
- Rocha-Filho, L. C., Ferreira-Caliman, M. J., Garófalo, C. A., & Augusto, S. C. (2018). A specialist in an urban area: Are cities suitable to harbour populations of the oligolectic bee *Centris* (Melacentris) collaris (Apidae: Centridini)? *Annales ZoologiciFennici*, 55(1–3), 135-149. Finnish Zoological and Botanical Publishing Board.
- Rodrigues, L. C., & Araujo, A. C. (2011). Comunidade de beija-flores e seusrecursosfloraisem um fragmentoflorestalurbano no Brasil. *Brazilian Journal of Biology*, 71(3), 611–622.

- Rodriguez-Riano, T., & Dafni, A. (2000). A new procedure to assess pollen viability. *Sexual Plant Reproduction*, 12(4), 241–244.
- Rogers, C. A. (1993). Application of aeropalynological principles in palaeoecology. *Review of Palaeobotany and Palynology*, 79(1-2), 133–140.
- Rogers, C. A., Wayne, P. M., Macklin, E. A., Muilenberg, M. L., Wagner, C. J., Epstein, P. R., & Bazzaz, F. A. (2006). Interaction of the onset of spring and elevated atmospheric CO₂ on ragweed (*Ambrosia artemisiifolia* L.) pollen production. *Environmental Health Perspectives*, 114(6), 865-869.
- Rojas-Gómez, M., Moral, J., López-Orozco, R., Cabello, D., Oteros, J., Barranco, D., & Díez, C. M. (2023). Pollen production in olive cultivars and its interannual variability. *Annals of Botany*, 132(6), 1145-1158.
- Rojo, J., & Pérez-Badia, R. (2015). Models for forecasting the flowering of Cornicabra olive groves. *International Journal of Biometeorology*, 59(11), 1547–1556.
- Rojo, J., Salido, P., & Pérez-Badia, R. (2015). Flower and pollen production in the ‘Cornicabra’ olive (*Olea europaea* L.) cultivar and the influence of environmental factors. *Trees*, 29(4), 1235–1245.
- Rosas-Guerrero, V., Aguilar, R., Martín-Rodríguez, S., Ashworth, L., Lopezaiza-Mikel, M., Bastida, J. M., & Quesada, M. (2014). A quantitative review of pollination syndromes: do floral traits predict effective pollinators?. *Ecology letters*, 17(3), 388-400.
- Rosell, P., Herrero, M., & Saúco, V. G. (1999). Pollen germination of cherimoya (*Annona cherimola* Mill.): In vivo characterization and optimization of in vitro germination. *Scientia Horticulturae*, 81(3), 251-265.
- Ross, J. J., Murfet, I. C., & Reid, J. B. (1997). Gibberellin mutants. *Physiologia Plantarum*, 100(3), 550–560.
- Russell, K. (2003). *EUFORGEN technical guidelines for genetic conservation and use for wild cherry (Prunus avium)*. International Plant Genetic Resources Institute.
- Sakai, S. (2002). A review of brood-site pollination mutualism: Plants providing breeding sites for their pollinators. *Journal of Plant Research*, 115(2), 161–168.

- Sakai, S., Momose, K., Yumoto, T., Kato, M., & Inoue, T. (1999). Beetle pollination of *Shorea parvifolia* (section Mutica, Dipterocarpaceae) in a general flowering period in Sarawak, Malaysia. *American Journal of Botany*, 86(1), 62–69.
- Sakar, E. H., Yamani, M. E., Boussakouran, A., & Rharrabti, Y. (2019). Reproductive phenology of some local almond (*Prunus dulcis* (Mill.) D.A. Webb) genotypes from northern Morocco. *Journal of Analytical Sciences and Applied Biotechnology*, 1(2), 49–54.
- Samant, S., Pant, S., Singh, M., Lal, M., Singh, A., Sharma, A., & Bhandari, S. (2007). Medicinal plants in Himachal Pradesh, northwestern Himalaya, India. *The International Journal of Biodiversity Science and Management*, 3(4), 234–251.
- Sánchez-Bayo, F., & Wyckhuys, K. A. (2019). Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation*, 232, 8–27.
- Sanjay Kumar, K., Prasad Khanduri, V., Kar, K., Mohan Sharma, C., & Kumar Riyal, M. (2016). Effect of growth regulators and time on in vitro pollen germination in three ornamental tropical tree species. *Journal of Agricultural Science and Technology*, 18(5), 1247–1255.
- Sanzol, J., & Herrero, M. (2001). The “effective pollination period” in fruit trees. *Scientia Horticulturae*, 90(1–2), 1–17.
- Sarvas, R. (1962). Investigations on the flowering and seed crop of *Pinus silvestris*. *Metsatieteellisen tutkimuslaitoksen julkaisu*, 53(4).
- Sarvella, P. (1961). Vital stain testing of pollen viability in cotton. *Journal of Heredity*, 55, 154.
- Sati, V. P. (2023). Forest Ecosystem Services and their Valuation in Mizoram, the Eastern Extension of the Himalaya. *Eco-feminism and Climate Change*, 4(2), 44–49.
- Saumitou-Laprade, P., Vernet, P., Vassiliadis, C., Hoareau, Y., de Magny, G., Dommée, B., & Lepart, J. (2010). A self-incompatibility system explains high male frequencies in an androdioecious plant. *Science*, 327(5973), 1648–1650.

- Scamoni, A. (1955). Beobachtungen über den Pollenflug der Waldbäume in Eberswalde. *Zeitschrift für Forstgenetik und Forstpflanzenzüchtung*, 4, 113–122.
- Schaal, B. A. (1980). Measurement of gene flow in *Lupinus texensis*. *Nature*, 284(5755), 450–451.
- Schemske, D. W., & Horvitz, C. C. (1984). Variation among floral visitors in pollination ability: a precondition for mutualism specialization. *Science*, 225(4661), 519–521.
- Schoenike, R. E., & Stewart, D. M. (1963). Fifth-year results of vacuum-drying storage and additives on the viability of some conifer pollens. *Forest Science*, 9(1), 96–97.
- Schwartz, G., Falkowski, V., & Peña-Claros, M. (2017). Natural regeneration of tree species in the Eastern Amazon: Short-term responses after reduced-impact logging. *Forest Ecology and Management*, 385, 97–103.
- Schweiger, O., Biesmeijer, J. C., Bommarco, R., Hickler, T., Hulme, P. E., Klotz, S., Kühn, I., Moora, M., Nielsen, A., Ohlemüller, R., Petanidou, T., Potts, S. G., Pyšek, P., Stout, J. C., Sykes, M. T., Tscheulin, T., Vilà, M., Walther, G.-R., Westphal, C., Winter, M., Zobel, M., & Settele, J. (2010). Multiple stressors on biotic interactions: How climate change and alien species interact to affect pollination. *Biological Reviews*, 85(4), 777–795.
- Seavey, S. R., & Bawa, K. S. (1986). Late-acting self-incompatibility in angiosperms. *The Botanical Review*, 52, 195–219.
- Setia, N., Setia, R. C., & Chabra, N. (1994). Interactive effects of growth hormones and calcium antagonists on germination and tube elongation of groundnut pollen. *Plant Cell Incompatibility Newsletter*, 26, 70–80.
- Seto, K. C., Parnell, S., & Elmqvist, T. (2013). A global outlook on urbanization. In *Urbanization, biodiversity and ecosystem services: Challenges and opportunities: A global assessment* (pp. 1–12). Springer.
- Severova, E., Kopylov-Guskov, Y., Selezneva, Y., Karaseva, V., Yadav, S. R., & Sokoloff, D. (2022). Pollen production of selected grass species in Russia and India at the levels of anther, flower and inflorescence. *Plants*, 11(3), 285.

- Sgolastra, F., Fisogni, A., Quaranta, M., Bogo, G., Bortolotti, L., & Galloni, M. (2016). Temporal activity patterns in a flower visitor community of *Dictamnus albus* in relation to some biotic and abiotic factors. *Bulletin of Insectology*, 69(2), 291–300.
- Shamsolshoara, Y., Gharesheikhabayat, R., Miri, S. M., Pirkhezri, M., & Davoodi, D. (2022). Floral morphology, pollen quality, and self-(in)compatibility in three natural *Prunus* interspecific hybrids. *Journal of Plant Physiology and Breeding*, 12(1), 109–122.
- Shamsolshoara, Y., Miri, S. M., Gharesheikhabayat, R., Pirkhezri, M., & Davoodi, D. (2023). Pollen viability and in vitro pollen germination in *Prunus* spp. Paper presented at the 5th International and 17th Iranian Genetic Congress, Tehran, Iran.
- Shanker, R. U., & Ganeshaiah, K. N. (1984). Does pollination efficiency shape the pollen grain to ovule ratio? *Current Science*, 53(14), 751–753.
- Sharma, C. M., & Khanduri, V. P. (2007). Pollen-mediated gene flow in Himalayan long needle pine (*Pinus roxburghii* Sargent). *Aerobiologia*, 23, 153–158.
- Sharma, D., & Abrol, D. P. (2014). Role of pollinators in sustainable farming and livelihood security. In D. P. Abrol (Ed.), *Beekeeping for poverty alleviation and livelihood security* (pp. 379–411). Springer.
- Sharma, M. (1970). An analysis of pollen loads of honey bees from Kangra, India. *Grana*, 10(1), 35–42.
- Shibata, M., Tanaka, H., Iida, S., Abe, S., Masaki, T., Niiyama, K., & Nakashizuka, T. (2002). Synchronized annual seed production by 16 principal tree species in a temperate deciduous forest, Japan. *Ecology*, 83(6), 1727–1742.
- Shivanna, K. R. (2003). *Pollen biology and biotechnology*. Science Publishers, Inc.
- Shivanna, K. R., & Ram, H. M. (1993). Pollination biology: contributions to fundamental and applied aspects. *Current science*, 226-233.
- Shivanna, K. R., & Tandon, R. (2014). *Reproductive Ecology of Flowering Plants: A Manual*. Springer India.
- Shivanna, K. R., & Rangaswamy, N. S. (2012). *Pollen biology: A laboratory manual*. Springer Science & Business Media.

- Shivanna, K. R., Linskens, H. F., & Cresti, M. (1991). Pollen viability and pollen vigor. *Theoretical and Applied Genetics*, 81(1), 38-42.
- Shukla, R. P., & Ramakrishnan, P. S. (1982). Phenology of trees in a sub-tropical humid forest in north-eastern India. *Vegetatio*, 49(2), 103–109.
- Silberbauer-Gottsberger, I., & Gottsberger, G. (1975). Übersphingophile Angiospermen Brasiliens / About sphingophilous Angiosperms in Brazil. *Plant Systematics and Evolution*, 157, 157-184.
- Silva, F. D. D. S., Carneiro, L. G., Aguirre-Gutiérrez, J., Lucotte, M., Guidoni-Martins, K., & Mertens, F. (2021b). Virtual pollination trade uncovers global dependence on biodiversity of developing countries. *Science Advances*, 7(11), eabe6636.
- Silva, J. L. S., de Oliveira, M. T. P., Cruz-Neto, O., Tabarelli, M., & Lopes, A. V. (2021a). Plant–pollinator interactions in urban ecosystems worldwide: A comprehensive review including research funding and policy actions. *Ambio*, 50, 884–900.
- Simpson, B. B. (1977). Breeding systems of dominant perennial plants of two disjunct warm desert ecosystems. *Oecologia*, 27, 203–226.
- Singh, D. P., Jermakow, A. M., & Swain, S. M. (2002). Gibberellins are required for seed development and pollen tube growth in *Arabidopsis*. *The Plant Cell*, 14(12), 3133–3147.
- Singh, K. P., & Kushwaha, C. P. (2006). Diversity of flowering and fruiting phenology of trees in a tropical deciduous forest in India. *Annals of Botany*, 97(2), 265-276.
- Singh, M., & Nautiyal, S. (1991). *Prunus cerasoides* (Himalayan wild cherry): A promising winter tree for fodder. *Indian Forester*, 117(7), 580-581.
- Singh, N. P., Singh, K. P., & Singh, D. K. (2002). *Flora of Mizoram* (Vol. 1). Botanical Survey of India.
- Singh, S., Singh, S. P., Singh, V., & Shikha, K. (2019). Studies on floral biology, fruit set and fruit drop of different genotypes of jamun (*Syzygium cumini* Skeels). *The Pharma Innovation Journal*, 8(1), 558–561.

- Smart, I. J., Tuddenham, W. G., & Knox, R. B. (1979). Aerobiology of grass pollen in the city atmosphere of Melbourne: effects of weather parameters and pollen sources. *Australian Journal of Botany*, 27(3), 333-342.
- Smith, F. E. (1951). Tetrazolium salt. *Science*, 113(2948), 751-754.
- Smith-Huerta, N. L., & Vasek, F. C. (1984). Pollen longevity and stigma pre-emption in *Clarkia*. *American Journal of Botany*, 71(9), 1183-1191.
- Snow, A. A., & Spira, T. P. (1991). Pollen vigour and the potential for sexual selection in plants. *Nature*, 352(6338), 796-797.
- Sondhi, S., & Kunte, K. (2018). *Butterflies and moths of Pakke Tiger Reserve* (2nd ed., vi+242 pp.). Titli Trust, National Centre for Biological Science, & Indian Foundation for Butterflies.
- Sondhi, S., & Kunte, K. (2014). *Butterflies and moths of Pakke Tiger Reserve* (vi+202 pp.). Titli Trust & Indian Foundation for Butterflies.
- Sondhi, S., Kunte, K., Agavekar, G., Lovalekar, R., & Tokekar, K. (2013). *Butterflies of the Garo Hills* (xvi+200 pp.). Samrakshan Trust, Titli Trust, & Indian Foundation for Butterflies.
- Soni, A., & Bohra, N. (2021). *Boswellia serrata*—Propagation and uses: A review. *International Journal of Advanced Research in Biological Sciences*, 8(5), 35-46.
- Soodan, A. S., Koul, A. K., & Wafai, B. A. (1989). Floral biology of almond (*Prunus amygdalus* L. Batsch) under cultivation in Kashmir Valley. *Proceedings of the Indian Academy of Sciences (Plant Sciences)*, 99(3), 297–300.
- Sorkheh, K., Shiran, B., Rouhi, V., & Khodambashi, M. (2011). Influence of temperature on the in vitro pollen germination and pollen tube growth of various native Iranian almonds (*Prunus* L. spp.) species. *Trees*, 25, 809-822.
- Southwick, E. E. (1984). Photosynthate allocation to floral nectar: A neglected energy investment. *Ecology*, 65(6), 1775–1779.
- Springer, C. J., & Ward, J. K. (2007). Flowering time and elevated atmospheric CO₂. *New Phytologist*, 176(2), 243-255.
- Ssymank, A., Kearns, C. A., Pape, T., & Thompson, F. C. (2008). Pollinating flies (Diptera): a major contribution to plant diversity and agricultural production. *Biodiversity*, 9(1-2), 86–89.

- Stanley, R. G., & Linskens, H. F. (1974). *Pollen: Biology, Biochemistry, and Management*. Springer.
- Stebbins, G. L. (1970). Adaptive radiation of reproductive characteristics in angiosperms, I: pollination mechanisms. *Annual Review of Ecology and Systematics*, 1(1), 307–326.
- Steffan-Dewenter, I., Münzenberg, U., Bürger, C., Thies, C., & Tschardt, T. (2002). Scale-dependent effects of landscape context on three pollinator guilds. *Ecology*, 83(5), 1421-1432.
- Stephenson, A. G. (1981). Flower and fruit abortion: proximate causes and ultimate functions. *Annual Review of Ecology and Systematics*, 12, 253-279.
- Stewart, A. B., & Waitayachart, P. (2020). Year-round temporal stability of a tropical, urban plant-pollinator network. *PLOS ONE*, 15, e0230490.
- Stewart, A. B., Sritongchuay, T., Teartisup, P., Kaewsomboon, S., & Bumrungsri, S. (2018). Habitat and landscape factors influence pollinators in a tropical megacity, Bangkok, Thailand. *PeerJ*, 6, e5335.
- Stiles, F. G. (1978). Temporal organization of flowering among the hummingbird foodplants of a tropical wet forest. *Biotropica*, 194-210.
- Stone, J. L., Thomson, J. D., & Dent-Acosta, S. J. (1995). Assessment of pollen viability in hand-pollination experiments: a review. *American Journal of Botany*, 82(9), 1186-1197.
- Stout, J. C., & Morales, C. L. (2009). Ecological impacts of invasive alien species on bees. *Apidologie*, 40(3), 388-409.
- Subramanya, S., & Radhamani, T. R. (1993). Pollination by birds and bats. *Current Science*, 65(3), 201-209. Special issue: Pollination Biology in Tropics.
- Sulusoglu, M., & Cavusoglu, A. (2014). In vitro pollen viability and pollen germination in cherry laurel (*Prunus laurocerasus* L.). *The Scientific World Journal*, 2014, 1-5.
- Sutyemez, M. (2011). Pollen quality, quantity and fruit set of some self-compatible and self-incompatible cherry cultivars with artificial pollination. *African Journal of Biotechnology*, 10(17), 3380-3386.
- Tanaka, T., & Nakao, S. (1976). *Tanaka's cyclopedia of edible plants of the world*. Keigaku Publishing.

- Tandon, R., Shivanna, K. R., & Mohan Ram, H. Y. (2003). Reproductive biology of *Butea monosperma*(Fabaceae). *Annals of Botany*, 92(5), 715-723.
- Tangtorwongsakul, P., Warrit, N., & Gale, G. A. (2018). Effects of landscape cover and local habitat characteristics on visiting bees in tropical orchards. *Agricultural and Forest Entomology*, 20(1), 28-40.
- Taylor, L. P., & Hepler, P. K. (1997). Pollen germination and tube growth. *Annual Review of Plant Biology*, 48(1), 461-491.
- Terborgh, J. (1987). Convergence vs. non-convergence in primate communities. In J. H. R. Gee & P. S. Giller (Eds.), *Organization of communities: Past and present* (pp. 231–246). Blackwell Scientific Publications.
- Teresa Gómez-Casero, M., Hidalgo, P. J., García-Mozo, H., Domínguez, E., & Galán, C. (2004). Pollen biology in four Mediterranean *Quercus* species. *Grana*, 43(1), 22-30.
- Tewari, B., and Tewari, A. (2016). Seed germination in *Prunus cerasoides* D. Don influenced by natural seed desiccation and varying temperature in Central Himalayan region of Uttarakhand, India. *International Journal of Bioassays*, 5(5), 4567-4572.
- Thakur, D., Rathore, N., Sharma, M. K., & Chawla, A. (2018). Enhanced reproductive success revealed key strategy for persistence of devastated populations in Himalayan food-deceptive orchid, *Dactylorhiza hatagirea*. *Plant Species Biology*, 33(3), 191-202.
- Thapa-Magar, K. B., Davis, T. S., Galbraith, S. M., & Grant-Hoffman, M. (2023). Effects of sage-grouse habitat restoration efforts on pollination networks in an arid ecosystem. *Rangeland Ecology & Management*, 91, 95-104.
- Thien, L. B. (1974). Floral biology of *Magnolia*. *American Journal of Botany*, 61(10), 1037–1045.
- Thien, L. B. (1980). Patterns of pollination in the primitive angiosperms. *Biotropica*, 12(1), 1-13.
- Thomson, J. D., Rigney, L. P., Karoly, K. M., & Thomson, B. A. (1994). Pollen viability, vigor, and competitive ability in *Erythronium grandiflorum* (Liliaceae). *American Journal of Botany*, 81(10), 1257-1266.

- Timerman, D., & Barrett, S. C. (2021). The biomechanics of pollen release: new perspectives on the evolution of wind pollination in angiosperms. *Biological Reviews*, 96(5), 2146-2163.
- Tiwari, P., Tiwari, J. K., & Ballabha, R. (2009). *P. cerasoides* (Himalayan Wild Cherry): A Boon to Hill-Beekeepers in Garhwal Himalaya. *Nature and Science*, 7(7), 21-23.
- Tomlinson, P. B. (1974). Breeding mechanisms in trees native to tropical Florida—a morphological assessment. *Journal of the Arnold Arboretum*, 55(2), 269–290.
- Towill, L. E., & Walters, C. (2000). Cryopreservation of pollen. In F. Engelmann & H. Takagi (Eds.), *Cryopreservation of Tropical Plant Germplasm* (pp. 115-129). IPGRI.
- Troup, R. S. (1921). *The Silviculture of Indian Trees* (Vol. 1). Clarendon Press.
- Tuell, J. K., & Isaacs, R. (2010). Weather during bloom affects pollination and yield of highbush blueberry. *Journal of Economic Entomology*, 103(3), 557–562.
- Tuinstra, M. R., & Wedel, J. (2000). Estimation of pollen viability in grain sorghum. *Crop Science*, 40(4), 968–970.
- Ullah, A., TlakGajger, I., Majoros, A., Dar, S. A., Khan, S., Shah, A. H., Khabir, M. N., Hussain, R., Khan, H. U., Hameed, M., & Anjum, S. I. (2021). Viral impacts on honey bee populations: A review. *Saudi Journal of Biological Sciences*, 28(1), 523–530.
- Ulyshen, M., & Horn, S. (2023). Declines of bees and butterflies over 15 years in a forested landscape. *Current Biology*, 33(7), 1346–1350.
- Ulyshen, M., Urban-Mead, K. R., Dorey, J. B., & Rivers, J. W. (2023). Forests are critically important to global pollinator diversity and enhance pollination in adjacent crops. *Biological Reviews*, 98(4), 1118–1141.
- Urban-Mead, K. R., Van Dyke, M., Muñiz, P., Young, A. D., Danforth, B. N., & McArt, S. H. (2023). Early spring orchard pollinators spill over from resource-rich adjacent forest patches. *Journal of Applied Ecology*, 60(3), 553–564.
- Uzun, A., Ünsal, H. T., & Pinar, H. (2023). Determination of pollen viability and pollen germination characteristics of some Sharka disease resistant apricot cultivars. *Current Trends in Natural Sciences*, 12(23), 274–278.

- Vamosi, J. C., Knight, T. M., Steets, J. A., Mazer, S. J., Burd, M., & Ashman, T.-L. (2006). Pollination decays in biodiversity hotspots. *Proceedings of the National Academy of Sciences of the United States of America*, 103(4), 956–961.
- Van der Pijl, L. (1961). Ecological aspects of flower evolution. II. Zoophilous flower classes. *Evolution*, 44-59.
- van Ginkel, M., & Flipphi, R. C. (2020). Why self-fertilizing plants still exist in wild populations: Diversity assurance through stress-induced male sterility may promote selective outcrossing and recombination. *Agronomy*, 10(3), 349.
- Van Leeuwen, W. M. (1933). *Biology of plants and animals occurring in the higher parts of Mount Pangrango-Gedeh in West-Java. Verhandelingen der Koninklijke Akademie van Wetenschappen*, 31, 1–273.
- Van Schaik, C. P., Terborgh, J. W., & Wright, S. J. (1993). The phenology of tropical forests: adaptive significance and consequences for primary consumers. *Annual Review of Ecology and Systematics*, 24(1), 353-377.
- Vanbergen, A. J. (2013). Threats to an ecosystem service: Pressures on pollinators. *Frontiers in Ecology and the Environment*, 11(5), 251–259.
- Vantheghem, P. H. (1869). Recherches physiologiques sur la végétation libre du pollen et de l'ovule et sur la fécondation directe des plantes. *Annales des Sciences Naturelles, Botanique*, 5, 312–329.
- Vargas Araujo, J., Andrade-Rodríguez, M., Villegas-Torres, Ó. G., Castillo-Gutiérrez, A., Colinas-León, M. T., Avitia-García, E., & Alia-Tejagal, I. (2017). Reproductive characteristics of nine varieties of poinsettia (*Euphorbia pulcherrima*, Willd. ex Klotzch). *Revista Mexicana de Ciencias Agrícolas*, 8(2), 295–306.
- Velayudhan, R., & Annadurai, R. S. (1986). Pollination potential of thrips (Insecta: Thysanoptera) in some Solanaceous plants. *Proceedings: Animal Sciences*, 95, 109–116.
- Vergotti, M. J., Fernández-Martínez, M., Kefauver, S. C., Janssens, I. A., & Peñuelas, J. (2019). Weather and trade-offs between growth and reproduction regulate fruit production in European forests. *Agricultural and Forest Meteorology*, 279, 107711.

- Vicente, A. R., Manganaris, G. A., Cisneros-Zevallos, L., & Crisosto, C. H. (2011). Prunus. In *Health-Promoting Properties of Fruit and Vegetables* (pp. 238-259). Wallingford, UK: CABI.
- Vinson, S. B., Frankie, G. W., & Barthell, J. (1993). Threats to the diversity of solitary bees in a neotropical dry forest in Central America. In J. LaSalle & I. D. Gauld (Eds.), *Hymenoptera and Biodiversity* (pp. 53-81). Wallingford, UK: CAB International.
- Visser, T. (1955). Germination and storage of pollen. *Mededelingen van de Landbouwhogeschool Wageningen*, 55, 1–68.
- Vitanova, I., Dimkova, S., & Ivanova, D. (2004). Vegetative and reproductive parameters of introduced plum cultivars. *Journal of Fruit and Ornamental Plant Research*, 12(Special ed.), 257–262.
- Viti, R., Bartolini, G., & Vitagliano, C. (1990). Growth regulators on pollen germination in olive. *Acta Horticulturae*, 286, 227–230.
- Vogel, S. (1974). *Öblumen und ölsammelnde Bienen* (Vol. 1). Akademie der Wissenschaften und der Literatur.
- Wadhwa, N., & Sihag, R. C. (2019). Flowering phenology of European plum (*Prunus domestica* L.) in the semi-arid environment of north-west India. *Asian Journal of Biological Sciences*, 12, 17–23.
- Walsh, N. E., & Charlesworth, D. (1992). Evolutionary interpretations of differences in pollen tube growth rates. *The Quarterly Review of Biology*, 67(1), 19-37.
- Wan, X., Sun, D., & Gao, C. (2024). Flower opening dynamics, pollen-ovule ratio, stigma receptivity and stigmatic pollen germination (in-vivo) in *Chaenomeles speciosa* (Sweet) Nakai. *Scientific Reports*, 14(1), 7127.
- Wang, M., Zhu, X., Peng, G., Liu, M., Zhang, S., Chen, M., & Zhou, H. (2022). Methylesterification of cell-wall pectin controls the diurnal flower-opening times in rice. *Molecular Plant*, 15(6), 956–972.
- Waser, N. M., & Price, M. V. (1981). Pollinator choice and stabilizing selection for flower color in *Delphinium nelsonii*. *Evolution*, 35(2), 376-390.
- Waser, N. M., & Price, M. V. (1983). Optimal and actual outcrossing in plants, and the nature of plant-pollinator interaction. In C. E. Jones & R. J. Little (Eds.),

- Handbook of experimental pollination biology* (pp. 341-359). Van Nostrand Reinhold.
- Waser, N. M., Chittka, L., Price, M. V., Williams, N. M., & Ollerton, J. (1996). Generalization in pollination systems, and why it matters. *Ecology*, 77(4), 1043-1060.
- Wells, D. R. (1988). Birds. In *Earl of Cranbrook* (Ed.), *Key environments: Malaysia* (pp. 167–195). Pergamon Press.
- Wenzel, A., Grass, I., Belavadi, V. V., & Tschardt, T. (2020). How urbanization is driving pollinator diversity and pollination—A systematic review. *Biological Conservation*, 241, 108321.
- Were, J. M., Munjuga, M., Simons, A. J., Dawson, I., & Ruigu, I. (2001). Reproductive biology of the endangered medicinal *Prunus africana* tree in Central Kenya. *East African Agricultural and Forestry Journal*, 67(1), 47–54.
- Werner, D. J., & Chang, S. (1981). Stain testing viability in stored peach pollen. *HortScience*, 16(4), 522–523.
- Wester, P., Stanway, R., & Pauw, A. (2009). Mice pollinate the Pagoda Lily, *Whiteheadia bifolia* (Hyacinthaceae)—First field observations with photographic documentation of rodent pollination in South Africa. *South African Journal of Botany*, 75(4), 713-719.
- Westgate, M. E., Lizaso, J., & Batchelor, W. (2003). Quantitative relationships between pollen shed density and grain yield in maize. *Crop Science*, 43(3), 934-942.
- Whelan, C. J., Şekercioğlu, Ç. H., & Wenny, D. G. (2015). Why birds matter: From economic ornithology to ecosystem services. *Journal of Ornithology*, 156, 227–238.
- Whelan, C. J., Wenny, D. G., & Marquis, R. J. (2008). Ecosystem services provided by birds. *Annals of the New York Academy of Sciences*, 1134(1), 25–60.
- Whitehead, D. R. (1983). Wind pollination: some ecological and evolutionary perspectives. In L. Real (Ed.), *Pollination biology* (pp. 97–108). Academic Press.

- Widrechner, M. P., Pellett, H. M., Ascher, P. D., & Fuhrman, S. C. (1983). in vivo pollen germination and vital staining in deciduous azaleas. *HortScience*, 18(1), 86–88.
- Williams, N. M., Minckley, R. L., & Silveira, F. A. (2001). Variation in native bee faunas and its implications for detecting community changes. *Conservation Ecology*, 5(1), 7.
- Wilson, R. J., Gutierrez, D., Gutierrez, J., & Monserrat, V. J. (2007). An elevational shift in butterfly species richness and composition accompanying recent climate change. *Global Change Biology*, 13(9), 1873–1887.
- Winfree, R., Bartomeus, I., & Cariveau, D. P. (2011). Native pollinators in anthropogenic habitats. *Annual Review of Ecology, Evolution, and Systematics*, 42, 1–22.
- Wojcik, V. A., & McBride, J. R. (2012). Common factors influence bee foraging in urban and wildland landscapes. *Urban Ecosystems*, 15, 581–598.
- Wright, S. J. (1991). Seasonal drought and the phenology of understory shrubs in a tropical moist forest. *Ecology*, 72(5), 1643–1657.
- Wright, S. J., & Cornejo, F. H. (1990). Seasonal drought and leaf fall in a tropical forest. *Ecology*, 71(3), 1165–1175.
- Yamaguchi, S., Smith, M. W., Brown, R. G., Kamiya, Y., & Sun, T. P. (1998). Phytochrome regulation and differential expression of gibberellin 3 β -hydroxylase genes in germinating *Arabidopsis* seeds. *The Plant Cell*, 10(12), 2115–2126.
- Yi, W., Law, S. E., McCoy, D., & Wetzstein, H. Y. (2006). Stigma development and receptivity in almond (*Prunus dulcis*). *Annals of Botany*, 97(1), 57–63.
- Yi, W., Law, S. E., McCoy, D., & Wetzstein, H. Y. (2006). Stigma development and receptivity in almond (*Prunus dulcis*). *Annals of Botany*, 97(1), 57–63.
- Zapata, T. R., & Arroyo, M. T. K. (1978). Plant reproductive ecology of a secondary deciduous tropical forest in Venezuela. *Biotropica*, 10(3), 221–230.
- Zariman, N. A., Omar, N. A., & Huda, A. N. (2022). Plant attractants and rewards for pollinators: Their significance to successful crop pollination. *International Journal of Life Sciences and Biotechnology*, 5(2), 270–293.

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List of publications

- **Phom, H. P.**, Kumar, K. S., Upadhyaya, K., Khanduri, V. P., Kumar, A., & Singh, A. B. (2025). Phyto-chemical, pharmacological, ethno-botanical and ecological importance of *Prunus cerasoides* D. Don. for human health and livelihood development: A review. *Environment and Ecology*, 43(3), 708–717.
- **Phom, H. P.**, Upadhyaya, K., & Hnamte, L. (2021). Nutrient content of leaf of three selected tree species of flood plains of Assam, India. *Indian Journal of Animal Nutrition*, 38(1), 105–108.
- Singh, A. B., Kumar, K. S., Kumar, S., Khanduri, V. P., & **Phom, H. P.** (2024). Nocturnal pollinators significantly contribute to tree bean (*Parkia timoriana* (DC.) Merr.) reproductive success compared to diurnal pollinators. *Journal for Nature Conservation*, 82, 126742.
- Singh, A. B., **Phom, H. P.**, Vanlalmalsawmropuia, H., Kumar, S., Khanduri, V. P., & Kumar, K. S. (2025). Argobiodiversity in traditional land-use systems of Northeast Indian part of Indo-Burma hotspot. In T. Pullaiah (Ed.), *Biodiversity hotspot of Indo-Burma* (in press). Apple Academic Press; CRC Press.

Presentation (Conference/ Seminar/ Workshop)

1. “Floral biology and pollen viability of *Prunus cerasoides* D. Don in tropical forest conditions of Mizoram, North -East India”. Presented at National Conference on Recent Advances in Plant Biology with Special References to North-East, India, organized by Department of Botany, School of Life Sciences, Mizoram University, Aizawl from April 20-21, 2023.
2. “A review on Ethnobotanical and Pharmacology Potential of Wild Himalayan Cherry Tree (*P. cerasoides* D. Don). Presented at 2nd Annual Convention of North East (India) Academy of Science and Technology (NEAST) & International Seminar on Recent Advances in Science and Technology (IRSRAST) from 16TH – 18th November 2020 (Virtual) organized by NEAST, Mizoram University, Aizawl, Mizoram (India).

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DEPARTMENT : Forestry
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ABSTRACT

**REPRODUCTIVE ECOLOGY OF *PRUNUS CERASOIDES* D.
DON IN TROPICAL AND TEMPERATE FOREST
CONDITIONS**

**AN ABSTRACT SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY**

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**DEPARTMENT OF FORESTRY
SCHOOL OF EARTH SCIENCES AND NATURAL RESOURCES
MANAGEMENT
AUGUST, 2025**

**REPRODUCTIVE ECOLOGY OF PRUNUS CERASOIDES D. DON IN
TROPICAL AND TEMPERATE FOREST CONDITIONS**

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**In partial fulfillment of the requirement of the Degree of Doctor of Philosophy
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Introduction

The *Prunus* genus, commonly known as stone fruits, encompasses around 430 species. These species are classified into five subgenera : *Amygdalus* (almonds and peaches), *Prunus* (plums and apricots), *Cerasus* (sweet and sour cherries), *Laurocerasus* (bay cherries), and *Padus* (bird cherries). Many commercially significant fruits such as peaches, plums, cherries, apricots, and almonds originated in Europe, western and central Asia, and China, later spreading across temperate regions. In India, 36 *Prunus* species have been identified, with 18 cultivated for various uses. Among these, *Prunus cerasoides* D. Don., also known as the Himalayan wild cherry, stands out for its ecological, cultural, and medicinal significance.

P. cerasoides is a deciduous tree belonging to the Rosaceae family, native to the subtropical and temperate Himalayas. It thrives at elevations between 1,200 and 2,400 meters, growing up to 10–11 meters tall. Its striking pinkish-white flowers bloom in late winter or early spring, providing a critical nectar source for pollinators like bees and butterflies when few other floral resources are available. The tree plays a vital role in forest ecosystems, supporting biodiversity by offering food and habitat for birds, small mammals, and insects.

Beyond its ecological role, *P. cerasoides* holds cultural and economic value. Its wood is prized for its durability and fragrance, used in making furniture, walking sticks, and umbrella handles. The flowers are sacred in Hindu rituals, and the fruit, though astringent, is used to make cherry brandy. Its bark, leaves, and seeds have been traditionally used to treat wounds, digestive disorders, asthma, and skin ailments. However, the plant contains cyanogenic glycosides, which can be toxic in high doses.

Despite its importance, *P. cerasoides* faces severe threats from habitat loss, deforestation, and climate change. Its wild populations are declining due to low seed germination rates and overexploitation for ornamental and commercial purposes. Currently listed as "Data Deficient" on the IUCN Red List, the species urgently

requires conservation efforts. Previous studies have focused on propagation and genetic diversity but comprehensive research on its reproductive ecology is essential for effective conservation which remains lacking.

Reproductive ecology examines how plants reproduce in response to environmental and biological factors, including pollination and mating systems. For *P. cerasoides*, understanding these dynamics is crucial because flowering phenology is tightly linked to temperature and rainfall. Climate-induced shifts in flowering time may disrupt pollination synchrony (Forrest & Miller-Rushing, 2010). Because successful reproduction is highly dependent on effective pollination, investigating how climate affects these interactions is key for conservation.

Objectives

This study was conducted on *P. cerasoides* growing at two contrasting location (Mizoram and Uttarakhand) with distinct forests i.e. tropical and temperate with the following objectives:

1. Comparison of annual variability in reproductive phenology of *Prunus cerasoides*.
2. Assessment of pattern of anthesis, anther dehiscence, stigma receptivity, pollinators availability and mating system in *Prunus cerasoides*
3. Evaluate pollen production, pollen viability and *in vitro* pollen germination in *Prunus cerasoides*.

Review of Literature

Reproductive phenology, which is the timing of flowering and fruiting, plays a crucial role in plant survival and ecosystem functioning. Climate change significantly influences these patterns by altering precipitation, temperature, and seasonal cycles. Plants with broad climatic adaptability often exhibit earlier flowering, while those in wetter environments may have prolonged reproductive phases. Tropical trees, in particular, show phenological shifts driven by evolutionary adaptations and photosynthetic pathways. Studies on *Prunus* species reveal diverse phenological responses, for example, local almond genotypes flower earlier than commercial varieties, indicating climate adaptation, while *P. cerasoides* in Indonesia flowers twice annually but rarely fruits. In addition, cherry bud dormancy and fruit development are temperature-dependent, and *P. domestica* in India exhibits consistent flowering periods. Climate-induced phenological shifts can disrupt pollinator-plant synchrony, which threatens reproductive success. For instance, *Rhododendron arboreum* in the Himalayas flowers earlier due to reduced winter precipitation, while *Dalbergia* species in Mexico suffer low fruit set despite mass flowering.

The mating systems of *Prunus* species are varied, but a reliance on cross-pollination is a common strategy. For instance, research on *P. cerasoides* has shown that it achieves a higher fruit set under cross-pollination. Other species depend on specific bees for pollination, and some cultivars exhibit strong self-incompatibility, requiring pollinizers for fruit set. Breeding systems vary from obligate outcrossing to facultative geitonogamy, a range that is influenced by floral traits and pollinator behaviour. Pollen limitation due to habitat fragmentation further reduces reproductive success. Floral traits such as color, scent, and nectar shape reproductive success through their interactions with pollinators. For example, some *Prunus* species attract bees, while others rely on insect pollinators, with scent and nectar as key attractants. Pollinator declines pose a global threat to plant reproduction, particularly in tropical forests where most trees depend on animals for pollination.

Pollen output varies by species, climate, and genetics. Temperate trees produce a high number of pollen grains per tree, while tropical species show lower but climatically adaptive pollen yields. For some cultivars, pollen production is genetically fixed. High pollen production enhances fertilization but is an energy-costly process, reflecting trade-offs in resource allocation. Pollen viability is critical for fertilization success. For instance, some pollen germinates best at a specific sucrose concentration, and pollen viability declines rapidly after the flower opens. Climate stressors like temperature and humidity can reduce pollen performance. Pollen-ovule (P/O) ratios are used to reflect mating strategies. High P/O ratios indicate a reliance on outcrossing, while low ratios suggest more efficient pollination. In some cases, elevation can increase P/O ratios due to pollinator scarcity. Pollinators are declining globally, impacting food security. *P. cerasoides* is known to support a diverse community of bees, and wild bees have been shown to enhance yields in other related species. Habitat loss, urbanization, and agrochemicals further threaten pollinator populations, underscoring the critical need for conservation efforts.

Materials and Methods

This study employed a comprehensive methodological framework to investigate the reproductive ecology of *P. cerasoides* across contrasting biogeographic regions - the tropical forests of Mizoram (23.73°N, 92.72°E) and temperate forests of Uttarakhand (30.18°N, 78.24°E). The research design incorporated field observations, controlled experiments, and laboratory analyses conducted from 2019-2022, with adaptations made for COVID-19 disruptions during 2020-2021.

Study Sites:

Two representative sites were selected based on their distinct bioclimatic characteristics:

1. **Mizoram:** Located in the Indo-Myanmar biodiversity hotspot with tropical monsoon climate (annual rainfall: 2,000-3,500 mm; temperature range: 11-34°C). Study plots were established in Aizawl district across elevations of

920-2,157 masl, featuring tropical wet evergreen and montane subtropical forests.

2. **Uttarakhand:** Situated in the Western Himalayas with temperate climate (annual rainfall: 1,550 mm; temperature range: -0.9-27.7°C). Research was conducted in Ranichauri, Tehri Garhwal (1,600-2,192 masl) dominated by Himalayan moist temperate forests with *Cedrus deodara* and *Quercus leucotrichophora*.

Methodology

The reproductive ecology of *Prunus cerasoides* was investigated across two distinct study sites. Reproductive phenology was monitored on ten randomly selected trees per site. The following parameters were evaluated for both individual plants and the entire population: flowering onset and duration, peak flowering (defined as the 50% bloom threshold), flowering synchrony (using Augspurger's index), and fruit set and drop rates. Weekly observations were conducted during the flowering seasons, which occurred from October to December in Mizoram and October to November in Uttarakhand.

For floral biology, anthesis patterns were recorded at 2-hour intervals for 50 flowers per site. Anther dehiscence was monitored microscopically across developmental stages, and stigma receptivity was assessed using a hydrogen peroxide peroxidase test. The pollination ecology was studied during the peak flowering season (15 days per site) by recording pollinator visitation frequency at 2-hour intervals. Pollinators were identified using taxonomic keys and photographic documentation.

Pollen biology was analyzed in the laboratory by estimating pollen production per flower and per plant using safranin-stained microscopy. Pollen viability was assessed through TTC staining, and *in vitro* germination experiments were conducted using Brewbaker & Kwack's medium with sucrose gradients and various growth regulators. The mating system was examined through six pollination treatments: natural pollination, autonomous selfing, hand self-pollination, open cross-pollination,

hand cross-pollination, and an apomixis control. Fruit set was compared using Lloyd & Schoen's index.

Climate data for the study period was obtained from ICAR-AICRPAM and the Mizoram Directorate of Science & Technology. This data included monthly maximum and minimum temperatures, relative humidity, and precipitation. All data were analyzed statistically using descriptive statistics, ANOVA for site and year effects, and Pearson correlations to identify relationships between climate and phenology. The study employed a randomized complete block design for the germination experiments and used standardized sampling protocols and replication to ensure the comparability and reliability of the data.

This integrated methodology enabled robust comparison of *P. cerasoides* reproductive strategies across contrasting ecosystems, providing insights into ecological adaptations to tropical and temperate environments. The multi-year design accounted for interannual variability while standardized protocols ensured data comparability between geographically distant sites.

Result

P. cerasoides is a medium-sized deciduous tree exhibiting characteristic floral traits, including bisexual flowers with a mean length of 21.92–22.00 mm and width of 29.67–29.70 mm, five sepals, and an average of 34–37 stamens per flower. Floral anthesis followed a diurnal pattern, peaking between 06:00–10:00 hours in Mizoram and 08:00–10:00 hours in Uttarakhand, correlating with temperature and humidity fluctuations. Stigma receptivity was highest during mid-morning (08:00–12:00 hours), while anther dehiscence peaked at 12:00–14:00 hours, demonstrating strong associations with rising temperatures ($r = 0.463$, $p < 0.01$) and declining humidity ($r = -0.563$, $p < 0.01$).

The mating system of *P. cerasoides* was assessed in both Mizoram and Uttarakhand and found to be partially self-compatible across the study years (2019 and 2021). In both regions, natural pollination consistently resulted in the highest fruit set. While cross-pollination also yielded high fruit set percentages, both hand and autonomous

self-pollination consistently produced a lower fruit set. The apomixis control resulted in zero fruit set, confirming that reproduction in the species is dependent on pollination. This pattern indicates that while the species is capable of self-pollination, it strongly favors cross-pollination for reproductive success. The Index of Self-Incompatibility (ISI) ranged between 0.79–0.95, confirming partial self-compatibility. The pollen-ovule ratio of *Prunus cerasoides* was found to be $43,092.85 \pm 5467.78$. According to Cruden's (1977) classification, this high ratio indicates a xenogamous breeding system, which is defined by a pollen-ovule ratio greater than 11,400. The study found significant variation in pollen production between the two sites, with the total pollen output per tree being notably higher in Uttarakhand (2.6×10^9 and 2.4×10^9 in 2019 and 2021, respectively) compared to Mizoram (1.2×10^9 and 1.8×10^9 in 2019 and 2021, respectively).

Phenological observations indicated regional variability in flowering onset (November–December in Mizoram; October–November in Uttarakhand), with flowering synchrony (0.75–0.81) and duration (24–35 days) influenced by climatic factors. Pollen viability varied between the two regions and increased from the pre-anthesis to anthesis stage in both. In Uttarakhand, viability was $52.29 \pm 5.78\%$ at the pre-anthesis stage, increasing to $66.42 \pm 5.51\%$ during anthesis. In Mizoram, viability was notably lower, at $28.05 \pm 4.61\%$ pre-anthesis, rising to $56.81 \pm 4.70\%$ at anthesis., and *in vitro* pollen germination was optimally induced by gibberellic acid (GA_3 , 8.71–9.15%) and kinetin (6.37–7.54%) at 100 mg L^{-1} .

The study identified a diverse range of pollinators, including birds, bees, wasps, and butterflies, for *P. cerasoides* in both Mizoram and Uttarakhand. The pollinator community overlap between the two sites was low, with only two species, *Pycnonotus cafer* and *Zosterops palpebrosus*, observed in both regions. In both locations, bird and hymenopteran activity was primarily diurnal, with visits peaking between 8:00 AM and 12:00 PM. A strong correlation was found between increasing temperature and heightened pollinator activity, suggesting that environmental factors significantly influence pollinator behavior. The diverse pollinator fauna highlights the species' importance as a floral resource. This study underscores the reproductive

adaptability of *P. cerasoides* to regional climates, its reliance on biotic pollinators, and the ecological significance of phenological synchrony. The findings provide insights into conservation strategies for this species, emphasizing habitat-specific pollination dynamics and climate-resilient traits.

Discussion

Reproductive Phenology

P. cerasoides exhibited marked regional and interannual variability in flowering phenology. In Uttarakhand, flowering occurred from late October to mid-November, while in Mizoram, it was delayed to November–December. This aligns with latitudinal and altitudinal gradients observed in temperate deciduous forests, where temperature not precipitation drives phenological shifts. Contrary to reports of biannual flowering in Indonesian populations, *P. cerasoides* in India flowered annually, suggesting climatic or genetic divergence. Flowering coincided with the leafless phase, a strategy likely enhancing pollinator visibility. Synchronization within populations (synchrony index: 0.75–0.81) promoted cross-pollination, though excessive synchrony may limit genetic exchange. Fruit set varied annually, with Uttarakhand outperforming Mizoram.

Floral Biology: Anthesis, Stigma Receptivity, and Anther Dehiscence

Anthesis followed diurnal rhythms, peaking at 06:00–08:00 in Mizoram and 08:00–10:00 in Uttarakhand, correlating with temperature ($r = -0.443$) and humidity ($r = 0.414$). Stigma receptivity was highest at 08:00–12:00, persisting until petal withering, contrasting with temperate *Prunus* species where receptivity often lags anthesis (Herrero, 1983). Anther dehiscence peaked at 12:00–14:00 via longitudinal slits, driven by rising temperatures ($r = 0.463$) and declining humidity ($r = -0.563$). These traits reflect adaptations to regional pollinator activity windows.

Mating System

The mating system of *P. cerasoides* was assessed and found to be partially self-compatible. Natural pollination consistently yielded the highest fruit set in both

Mizoram ($60.05\% \pm 2.41$) and Uttarakhand ($70.45\% \pm 1.80$). While cross-pollination treatments produced a high fruit set, both hand and autonomous self-pollination consistently resulted in a lower fruit set. Importantly, apomixis was absent, confirming that reproduction in the species is dependent on pollination. This pattern indicates that while the species is capable of self-pollination, it strongly favors cross-pollination for reproductive success. These results mirror trends in *Schima wallichii* and *Prunus dulcis*, highlighting the genus's preference for outcrossing.

Pollen Production

Pollen production for *P. cerasoides* varied significantly between the two regions. In Mizoram, the estimated average pollen production per tree was 1.2×10^9 and 1.8×10^9 in 2019 and 2021, respectively. In Uttarakhand, pollen output was consistently higher, recorded at 2.6×10^9 and 2.4×10^9 in the same years. Pollen/ovule ratios ($43,092.85 \pm 5467.78$) aligned with xenogamy.

Pollinator Availability

Pollinator guilds differed significantly between regions. In Mizoram, seven bird species (e.g., *Zosterops palpebrosus*), three hymenopterans (*Apis cerana*), and seven lepidopterans (*Delias* spp.) dominated, with peak activity at 10:00–12:00. Uttarakhand hosted 13 bird species (*Pycnonotus leucogenys*) and two hymenopterans (*Bombus haemorrhoidalis*), active at 08:00–10:00. Birds were primary pollinators, transferring pollen via head/breast contact. Butterfly diversity was higher in Mizoram, while bird richness peaked in Uttarakhand. Pollinator shifts between years (*Pycnonotus cafer* to *Zosterops palpebrosus* in Mizoram) suggested climate-mediated resource partitioning.

Pollen Viability and *In Vitro* Pollen Germination

Pollen viability was higher at anthesis (Mizoram: 56.81%; Uttarakhand: 66.42%) than pre-anthesis (TTC assay). *In vitro* pollen germination was low in controls but improved with sucrose (5–10%) and growth hormones. Gibberellic acid (GA_3 : 100 mg L⁻¹) maximized germination (Mizoram: 8.71%; Uttarakhand: 9.15%), followed

by kinetin (6.37–7.54%). IAA and IBA were less effective, indicating hormone-specific responses. Regional differences in germination efficiency highlighted environmental modulation of pollen performance.

Summary and Conclusion

The study revealed distinct phenological patterns between the two regions, with flowering occurring during winter months but showing regional variations in timing. In Mizoram, peak flowering was observed between 0600-0800 hours, while in Uttarakhand it occurred slightly later (0800-1000 hours). This temporal shift correlated strongly with local microclimatic conditions, particularly temperature and humidity regimes. The species demonstrated remarkable flowering synchrony (index: 0.75-0.81) within populations, a strategy that enhances pollinator attraction while potentially limiting gene exchange among individuals.

Pollen biology studies demonstrated the species' high reproductive potential, with substantial pollen production and consistent viability. *In vitro* pollen germination experiments confirmed pollen functionality, with optimal germination achieved using sucrose solutions (5-10%) and specific growth hormones (particularly GA₃ and kinetin), reaching up to 9.15% success rates. These findings indicate that pollen quality and quantity are not limiting factors in the species' reproductive process.

Controlled pollination experiments established that *P. cerasoides* exhibits partial self-compatibility (Index of Self-Incompatibility: 0.79-0.95). Natural pollination yielded the highest fruit set followed by cross-pollination treatments while self-pollination and geitonogamy showed significantly lower success rates. The complete absence of fruit set under apomictic conditions confirmed the species' obligate requirement for biotic pollen transfer.

Pollinator observations documented a diverse assemblage of 21 bird species, 6 lepidopterans, 4 hymenopterans, and a squirrel, demonstrating a mixed pollination system combining ornithophily and entomophily. Passerine birds (*Pycnonotus cafer*, *Zosterops palpebrosus*) emerged as particularly effective pollinators due to their consistent contact with reproductive structures during nectar feeding. Regional

variations were notable, with Mizoram showing greater butterfly diversity and Uttarakhand exhibiting richer avian pollinator communities. Pollinator activity peaked during mid-morning hours, closely synchronized with anthesis timing.

Conclusion

P. cerasoides exhibits significant ecological adaptability, with regional variations in flowering phenology and pollinator interactions that enable successful reproduction across tropical and temperate environments. Its reproductive strategy is marked by a partial self-compatibility system, which balances the benefits of outcrossing for genetic diversity with reproductive assurance, while abundant pollen production supports effective pollination and fruit set. The species relies strongly on a wide range of biotic pollinators, particularly birds and insects, making it vulnerable to pollinator declines and highlighting the importance of integrated conservation approaches. Its reproductive phenology shows clear correlations with climatic conditions such as temperature and humidity, suggesting sensitivity to changing environmental patterns. Moreover, by flowering in winter and providing vital resources when few alternatives are available, *P. cerasoides* serves as a keystone species across its native habitats, from the Himalayan region to the forests of northeast India, sustaining pollinator communities during resource-scarce periods.