

**REPRODUCTIVE BIOLOGY OF *PARKIA TIMORIANA* (DC.)
MERR. UNDER SILVIHORTICULTURAL SYSTEM IN
MIZORAM, NORTH-EAST INDIA**

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

AKOIJAM BENJAMIN SINGH

MZU REGISTRATION No.: 2200139

Ph.D. REGISTRATION No.: MZU/Ph.D./1910 of 20.08.2021



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

**REPRODUCTIVE BIOLOGY OF *PARKIA TIMORIANA* (DC.) MERR.
UNDER SILVIHORTICULTURAL SYSTEM IN MIZORAM, NORTH-EAST
INDIA**

By

AKOIJAM BENJAMIN SINGH

Department of Forestry

Supervisor

Dr. NAGARAJ HEGDE

Joint Supervisor

Dr. KEWAT SANJAY KUMAR

Submitted

**In partial fulfillment of the requirement of the Degree of Doctor of Philosophy
in Forestry of Mizoram University, Aizawl.**



Mizoram University

Department of Forestry
School of Earth Sciences and
Natural Resources Management
Aizawl- 796004, Mizoram, India

CERTIFICATE

This is to certify that the thesis entitled “**Reproductive biology of *Parkia timoriana* (DC.) Merr. under silvihorticultural system in Mizoram, North-East India**” submitted by **Mr. Akoijam Benjamin Singh** for the award of the degree of **Doctor of Philosophy in Forestry** of Mizoram University, Aizawl, embodies the record of original investigation carried out by him under my supervision. He has duly registered and the thesis presented is worth of being considered for the award of the Ph.D. degree. The work has not been submitted for any degree to any other University.

Date:

Place: Aizawl

(Dr. Nagaraj Hegde)
Supervisor
Department of Forestry
Mizoram University
Aizawl, Mizoram


Dr. Kewat Sanjay Kumar
Associate Professor
Dept. of Botany, University of Allahabad
Prayagraj-211002
(Dr. Kewat Sanjay Kumar)
Joint Supervisor
Department of Botany
University of Allahabad
Prayagraj, Uttar Pradesh

Declaration of the Candidate

Mizoram University

August, 2025

I, **Akoijam Benjamin Singh**, hereby declare that the thesis entitle “**Reproductive biology of *Parkia timoriana* (DC.) Merr. under silvihorticultural system in Mizoram, North-East India**” is the record of original work done by me, that the contents of this thesis did not form basis of the award of my previous degree or to the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/ Institute.

This is being submitted to the Mizoram University for the Degree of Doctor of Philosophy in Forestry.

(Akoijam Benjamin Singh)

Research Scholar

Department of Forestry

Mizoram University

Aizawl, Mizoram

(Dr. Nagaraj Hegde)

Supervisor

Department of Forestry

Mizoram University

Aizawl, Mizoram



Dr. Kewat Sanjay Kumar
Associate Professor
Dept. of Botany, University of Allahabad
Prayagraj-211002

(Dr. Kewat Sanjay Kumar)

Joint Supervisor

Department of Botany

University of Allahabad

Prayagraj, Uttar Pradesh

(Prof. U. K. Sahoo)

Head

Department of Forestry

Mizoram University

Aizawl, Mizoram

ACKNOWLEDGEMENTS

I would like to express my sincere and heartfelt gratitude to my supervisor, Dr. Nagaraj Hegde, Department of Forestry, Mizoram University, and my joint supervisor, Dr. Kewat Sanjay Kumar, Department of Botany, University of Allahabad. Their unwavering support throughout every phase of this challenging study has been invaluable. Without their expert guidance, insightful counsel, constant encouragement, and advice, this work would not have been possible. I am deeply thankful for their relentless drive to push me towards my best and for inspiring a genuine passion for learning within me.

I extend my sincere appreciation to all the faculty members of my department, including Prof. U.K. Sahoo, Prof. S.K. Tripathi, Prof. Lalnundanga, Prof. Kalidas Upadhaya, Prof. Shyam S. Phartyal, Dr. Keshav Kumar Upadhyay, Dr. David C. Vanlalfakawma, and Dr. Anudip Gogoi, for their continuous guidance, encouragement, and support, which have been instrumental to my success.

I am also immensely grateful to Dr. Naorem Bidyaleima Chanu, whose contributions have significantly shaped the outcome of my work. Her tireless moral support and encouragement throughout the various stages of my research have been deeply appreciated.

A special thank you to my seniors, Dr. Uttam Thangjam, Dr. Ngangbam Somen Singh, and my friends Dr. Puyam Devanda Singh, H. Vanlalmalsawmropuia, HENCHAI P. PHOM, and Rajdeep Chanda for their constant assistance and support, which played an essential role in the successful completion of my research.

I would also like to express my heartfelt thanks to Aunty H.B. Sophia, H.B. Zohmingthanga, and H.B. Rosy for their invaluable help and support during my research journey.

I extend my most sincere and profound thanks to my beloved parents, Mr. Akoijam Ibotomba Singh and Mrs. Akoijam Pusparani Devi, as well as my brothers, Dr. Jelson Akoijam and Honish Akoijam, for their unwavering support through every challenge and success in my life.

Lastly, I offer my sincerest gratitude to Almighty God, whose blessings, grace, and mercy have allowed me to complete this thesis on time. I humbly offer my heartfelt prayers and thanks to Him.

Date:

Place: Aizawl

(Akoijam Benjamin Singh)

<i>Contents</i>	<i>Page No.</i>
<i>Certificate</i>	<i>i</i>
<i>Declaration</i>	<i>ii</i>
<i>Acknowledgement</i>	<i>iii</i>
<i>Table of Contents</i>	<i>iv-xi</i>
<i>List of Tables</i>	<i>xii-xiii</i>
<i>List of Figures</i>	<i>xiv -xix</i>
<i>List of Abbreviations</i>	<i>xx-xxi</i>
Chapter 1: Introduction	1-20
1.1. Impact of anthropogenic activities on tropical ecosystem reproductive dynamics	1-2
1.2. Importance of reproductive interactions in plant ecology	2-4
1.3. Reproductive biology in conservation efforts	4-5
1.4. Role of phenology in plant reproductive success	5-7
1.5. Significance of breeding systems in plants reproduction	7-9
1.6. Role of floral biology in pollination success	9-11
1.7. Pollination and its ecosystem impact	11-12
1.8. Pollen-pistil interaction and reproductive barriers	12-14
1.9. Factors influencing reproductive success	14-16
1.10. Challenges in studying reproductive biology of trees	16-18
1.11. Threats to pollination systems	18-20
1.12. Objectives	20
Chapter 2: Review of Literature	21-45
2.1. Role of plant reproductive biology in conservation	21-24
2.2. Phenology of flowering plants: reproductive timing and environmental impacts	24-27
2.3. Impact of climatic variables on phenophase events	27-29
2.4. Floral biology of plants	29-31
2.5. Floral volatiles and nectar as pollinator attractants	31-33
2.6. Pollen biology in flowering plants	33-34
2.7. Pollen-ovule ratio of plants	34
2.8. Techniques for assessing pollen viability in plants	34-38
2.9. <i>In vitro</i> pollen germination techniques in plants	38-39
2.10. Stigma receptivity and its role in plant fertilization	39-40

2.11. Pollination ecology: roles of animal pollinators in plant reproduction	40-44
2.12. Plant breeding systems and their role in pollination and seed production	44-45
Chapter 3: Study Site	46-52
3.1. Mizoram	46
3.1.1. Geographical location	46-48
3.1.2. Climate	48
3.1.3. Characteristics of the soil	49
3.1.4. Vegetation and forest	49-50
3.1.5. Agriculture	50-51
3.1.6. Agroforestry	51-52
3.1.7. Demography	52
Chapter 4: Materials and methods	53-69
4.1. Monitoring of reproductive phenology	53-54
4.1.1. Onset (Floral initiation)	54
4.1.2. Duration of flowering	54
4.1.3. Peak flowering	54
4.1.4. Mean flowering amplitude	55
4.1.5. Fruit formation	55
4.1.6. Flowering synchrony	55
4.2 Impact of climatic variables on phenophase events	55-56
4.3. Floral biology	56
4.3.1. Anthesis time and anther dehiscence pattern	56
4.3.2. Stigma receptivity analysis	56-57
4.4. Pollen morphology examination	57-58
4.5. Pollinators and their foraging behaviour	58
4.6. Mating systems	58-59
4.6.1. Natural/ Open pollination (Control)	59
4.6.2. Autogamy (Self Pollination)	59
4.6.3. Geitonogamous pollination	59
4.6.4. Xenogamous pollination	59
4.7. Relative contribution of nocturnal and diurnal pollinators to the reproductive success of <i>P. timoriana</i> .	60

4.7.1. Experimental design and pollinator treatments	60
4.7.1.1. Diurnal pollination	60
4.7.1.2. Nocturnal pollination	60
4.7.1.3. Open pollination	60
4.7.1.4. Pollinator exclusion	60-63
4.7.2. Harvesting and yield measurements	63
4.8. Pollen production, pollen- ovule ratio and pollen volume	63
4.8.1. Pollen production and pollen- ovule ratio	63-64
4.8.2. Pollen volume	64
4.9. Air-borne pollen density	64
4.9.1. Slide hanging method	64-65
4.9.2. GRIPS-99M Rotation Impaction Sampler	65
4.10. Analysis of pollen viability	65-66
4.11. Nectar analysis	66
4.11.1. Nectar volume	66
4.11.2. Concentration of nectar	66
4.11.3. Amount of nectar sugars	67
4.11.4. Energetic value of nectar	67
4.11.5. Analysis of sugars in nectar sample using HPLC	67
4.11.6. Analysis of amino acids in nectar sample using HPLC	68
4.12. <i>In vitro</i> pollen germination	68
4.12.1. Effect of sucrose and plant growth regulators on pollen germination	68-69
4.12.2. Effect of temperature treatments on pollen germination and pollen tube growth	69
4.13. Statistical analysis	69
Chapter 5: Results	70-245
5.1. Monitoring of reproductive phenology	70
5.1.1. Reproductive phenology of <i>P. timoriana</i> across three sites (Sairang, Tanhril, and Reiek), Mizoram, India from 2021 to 2024	70
5.1.1.1. Onset of flowering	70-71
5.1.1.2. Flowering duration	71
5.1.1.3. Peak of flowering	71-72
5.1.1.4. Amplitude of flowering	72

5.1.1.5. Flowering synchrony	72
5.1.1.6. Fruit formation	73-74
5.1.2. Codification of BBCH scale in reproductive biological events of <i>P. timoriana</i>	75-78
5.1.3. Correlation of reproductive phenological events with environmental parameters	78-81
5.1.4. Simple regression analysis	82
5.1.5. Stepwise multiple regression analysis of different reproductive phenological events vs environmental parameters	82-87
5.1.6. Stepwise multiple regression analysis of different reproductive phenological events and environmental parameters	87-89
5.2. Floral biology	89-90
5.2.1. Anthesis	91-92
5.2.2. Pattern of anther dehiscence	93-95
5.2.3. Stigma receptivity	95-97
5.2.4. Correlation of floral biology parameters with climatic variables	97-99
5.2.5. Stepwise regression modelling of floral biology parameters w.r.t. climatic variables	99-101
5.3. Morphology of pollen in <i>P. timoriana</i>	101-103
5.4. Pollinators behaviour	103
5.4.1. Visitation frequency of <i>Camponotus spp.</i>	103-108
5.4.2. Visitation frequency of <i>Tapinoma sessile</i>	108-110
5.4.3. Visitation frequency of <i>Bombus bicoloratus</i>	110-112
5.4.4. Visitation frequency of <i>Apis cerana indica</i>	112-113
5.4.5. Visitation frequency of <i>Trigona spp.</i>	114-115
5.4.6. Visitation frequency of <i>Vespa affinis</i>	115-117
5.4.7. Visitation frequency of <i>Phimenes flavopictus</i>	117-119
5.4.8. Visitation frequency of <i>Achaea serva</i>	119-121
5.4.9. Visitation frequency of <i>Agrotis infusa</i>	121-123
5.4.10. Visitation frequency of <i>Ercheia cyllaria</i>	123-125
5.4.11. Visitation frequency of <i>Eudocima phalonia</i>	125-126
5.4.12. Visitation frequency of <i>Hulodes caranea</i>	127-128
5.4.13. Visitation frequency of <i>Psyrassa unicolor</i>	128-130

5.4.14. Visitation frequency of <i>Ariadne merione</i>	130-132
5.4.15. Visitation frequency of bats	132-134
5.4.16. Visitation frequency of each pollinator for the year 2021 and 2022.	134-136
5.4.17. Visitation frequency of each pollinator for the year 2021 and 2022 as per family wise.	136-138
5.4.18. Visitation frequency of each pollinator for the year 2021 and 2022 as per order wise.	138-139
5.4.19. Spearman's rank correlation coefficient of pollinators and climatic variables	140-153
5.5. Mating system	153
5.5.1. Fruit formation % of autogamy, open pollination, geitonogamy, and xenogamy in 2021, 2022, and 2023	153-155
5.5.2. Effect of mating systems (autogamy, open pollination, geitonogamy, and xenogamy) on fruit formation.	155-156
5.6. Relative contribution of nocturnal and diurnal pollinators to the reproductive success of <i>P. timoriana</i>	156-158
5.7. Pollen production, pollen-ovule ratio and pollen volume	159
5.7.1. Pollen production and pollen ovule ratio	159
5.7.1.1. Effect of sites on pollen production and pollen ovule ratio	159
5.7.1.1.1. No. of inflorescences per tree	159-161
5.7.1.1.2. No. of flowers per inflorescence	161-162
5.7.1.1.3. No. of nectar secreting flowers	162-163
5.7.1.1.4. No. of hermaphrodite flowers	163-164
5.7.1.1.5. No. of anthers per flower	165
5.7.1.1.6. No. of pollen per anther	165-167
5.7.1.1.7. No. of flowers per tree	167-169
5.7.1.1.8. No. of nectar secreting flowers per tree	169
5.7.1.1.9. No. of hermaphrodite flowers per tree	169-171
5.7.1.1.10. No. of pollen per hermaphrodite flower	171-172
5.7.1.1.11. No. of pollen per inflorescence	172-173
5.7.1.1.12. No. of pollen per tree	173-174
5.7.1.1.13. No. of ovules per flower	174-176
5.7.1.1.14. Pollen ovule ratio	176-177

5.7.1.2. Effect of years on pollen production and pollen ovule ratio	177
5.7.1.2.1. No. of inflorescences per tree	177
5.7.1.2.2. No. of flowers per inflorescence	177-179
5.7.1.2.3. No. of nectar secreting flowers	179-181
5.7.1.2.4. No. of hermaphrodite flowers	181-182
5.7.1.2.5. No. of anthers per flower	182
5.7.1.2.6. No. of pollen per anther	182-184
5.7.2.7. No. of flowers per tree	184-186
5.7.1.2.8. No. of nectar secreting flowers per tree	186
5.7.1.2.9. No. of hermaphrodite flowers per tree	187
5.7.1.2.10. No. of pollen per hermaphrodite flower	187-189
5.7.1.2.11. No. of pollen per inflorescence	189-191
5.7.1.2.12. No. of pollen per tree	191
5.7.1.2.13. No. of ovules per flower	192
5.7.1.2.14. Pollen ovule ratio	192-194
5.7.1.2.15. Spearman's rank correlation analysis between floral and pollen productivity for Sairang, Tanhril, and Reiek.	194-201
5.7.2. Pollen grain size and volume	201-202
5.8. Air-borne pollen density	202
5.8.1. Slide hanging method	202-203
5.8.2. GRIPS-99M Rotation Impaction Sampler	203-205
5.8.3. Spearman's rank correlation analysis between concentration of pollen grains and environmental parameters	206-208
5.9. Analysis of pollen viability	208
5.9.1. Comparison of pollen viability test by using TTC, FDA, and Alexander staining for hermaphrodite flower and nectar secreting flower.	208-210
5.9.2. Comparison of pollen viability test between hermaphrodite flower and nectar secreting flower.	210-211
5.10. Nectar analysis	211
5.10.1. Concentration of nectar	211-213
5.10.2. Amount of nectar sugar collected hourly	213-214
5.10.3. Amount of nectar collected	214-216
5.10.4. Nectar energetics value	216

5.10.5. Amount of nectar collected (ml) daily per inflorescence	217
5.10.6. Analysis of sugars in nectar using HPLC	218
5.10.7. Analysis of amino acids in nectar using HPLC	218-221
5.10.8. Spearman's rank correlation analysis between different nectar properties and environmental parameters studied.	221-224
5.11. <i>In vitro</i> pollen germination	224
5.11.1. Effect of distilled water and sucrose on <i>in vitro</i> pollen germination w.r.t. time block.	224-225
5.11.2. Effect of time on <i>in vitro</i> pollen germination w.r.t. distilled water and sucrose.	226-227
5.11.3. Effect of distilled water and sucrose on <i>in vitro</i> pollen germination.	227-228
5.11.4. Effect of different conc. of IAA on <i>in vitro</i> pollen germination w.r.t. time.	228-230
5.11.5. Effect of time on <i>in vitro</i> pollen germination w.r.t. diff. conc. of IAA.	230
5.11.6. Effect of different conc. of IBA on <i>in vitro</i> pollen germination w.r.t. time.	231
5.11.7. Effect of time on <i>in vitro</i> pollen germination w.r.t. diff. conc. of IBA.	231-233
5.11.8. Effect of different conc. of K on <i>in vitro</i> pollen germination w.r.t. time.	233-235
5.11.9. Effect of time on <i>in vitro</i> pollen germination w.r.t. diff. conc. of K.	235
5.11.10. Effect of different conc. of GA on <i>in vitro</i> pollen germination w.r.t. time.	236-242
5.11.11. Effect of time on <i>in vitro</i> pollen germination w.r.t. diff. conc. of GA ₃ .	236-238
5.11.12. Effect of different conc. of plant growth regulators on <i>in vitro</i> pollen germination.	238-240
5.11.13. Effect of different plant growth regulators on <i>in vitro</i> pollen germination.	240
5.11.14. Spearman's rank correlation analysis between concentration, time, sucrose, and hormones.	241

5.11.15. Effect of temperature on <i>in vitro</i> pollen germination.	241-244
5.11.16. Effect of temperature on pollen tube length.	244
5.11.17. Spearman's rank correlation analysis between temperature, pollen germination and pollen tube length.	245
Chapter 6: Discussions	246-271
6.1. Reproductive phenology of <i>P. timoriana</i> : spatio-temporal variation across different elevations	246-249
6.2. Floral biology of <i>P. timoriana</i> : temporal dynamics of anthesis, anther dehiscence, and stigma receptivity	249-251
6.3. Pollen morphology of <i>P. timoriana</i>	251-253
6.4. Pollinator behavior and visitation patterns	253-255
6.5. Mating system dynamics	256-258
6.6. Role of diurnal and nocturnal pollinators in the reproductive success of <i>P. timoriana</i>	258-259
6.7. Spatiotemporal dynamics of pollen production and floral traits	260-262
6.8. Temporal variability in pollen concentrations	262-263
6.9. Evaluating pollen viability in floral morphs	263-265
6.10. Nectar secretion dynamics in <i>P. timoriana</i>	265-268
6.11. Optimizing <i>in vitro</i> pollen germination	268-271
Chapter 7: Summary and conclusions	272-277
References	278-328
Brief biodata of candidates	329
List of publications and conference attended	330-334
Particulars of candidate	335

List of Tables

Table No.	Description	Page no.
Table 5.1.	Reproductive phenology of <i>P. timoriana</i> for the site Sairang.	73
Table 5.2.	Reproductive phenology of <i>P. timoriana</i> for the site Tanhril.	74
Table 5.3.	Reproductive phenology of <i>P. timoriana</i> for the site Reiek.	74
Table 5.4.	Spearman's rank correlation analysis between different reproductive phenological events and environmental parameters studied.	80
Table 5.5.	Simple regression between the different reproductive phenological events and environmental parameters studied.	83-85
Table 5.6.	Tabulated results of multiple linear regression of different reproductive phenological events vs environmental parameters studied.	86
Table 5.7.	Tabulated results of multiple linear regression of different reproductive phenological events and environmental parameters studied.	88
Table 5.8.	Spearman's rank correlation analysis between different floral biology parameters and environmental parameters studied for the year 2021.	98
Table 5.9.	Spearman's rank correlation analysis between different floral biology parameters and environmental parameters studied for the year 2022.	100
Table 5.10.	Regression models of floral biology parameters with climatic variables.	100
Table 5.11.	Spearman's rank correlation analysis between Time, <i>Camponotus</i> spp., <i>Tapinoma sessile</i> , <i>Bombus bicoloratus</i> , <i>Apis cerana indica</i> , <i>Trigona</i> spp., <i>Vespa affinis</i> , <i>Phimenes flavopictus</i> , <i>Achaea serva</i> , <i>Agrotis infusa</i> , <i>Ercheia cyllaria</i> , <i>Eudocima phalonia</i> , <i>Hulodes caranea</i> , <i>Psyrassa unicolor</i> , <i>Ariadne merione</i> , bat, and climatic variables for 2021.	141-146
Table 5.12.	Spearman's rank correlation analysis between Time, <i>Camponotus</i> spp., <i>Tapinoma sessile</i> , <i>Bombus bicoloratus</i> , <i>Apis cerana indica</i> , <i>Trigona</i> spp., <i>Vespa affinis</i> , <i>Phimenes flavopictus</i> , <i>Achaea serva</i> , <i>Agrotis infusa</i> , <i>Ercheia cyllaria</i> , <i>Eudocima phalonia</i> , <i>Hulodes caranea</i> , <i>Psyrassa unicolor</i> , <i>Ariadne merione</i> , bat, and climatic variables for 2022.	147-152

Table 5.13.	Spearman's rank correlation coefficient between total no. of seeds per pod, total no. of pods per capitulum, seed length, weight of each seed, and seed diameter.	158
Table 5.14.	Spearman's rank correlation analysis between number of inflorescences per tree, flowers per inflorescence, nectar secreting flowers, hermaphrodite flowers, pollen per anther, total flowers per tree, total nectar secreting flowers per tree, total hermaphrodite flowers per tree, total pollen per hermaphrodite flower, total pollen per inflorescence, and total pollen per tree for Sairang.	195-196
Table 5.15.	Spearman's rank correlation analysis between number of inflorescences per tree, flowers per inflorescence, nectar secreting flowers, hermaphrodite flowers, pollen per anther, total flowers per tree, total nectar secreting flowers per tree, total hermaphrodite flowers per tree, total pollen per hermaphrodite flower, total pollen per inflorescence, and total pollen per tree for Tanhril.	197-198
Table 5.16.	Spearman's rank correlation analysis between number of inflorescences per tree, flowers per inflorescence, nectar secreting flowers, hermaphrodite flowers, pollen per anther, total flowers per tree, total nectar secreting flowers per tree, total hermaphrodite flowers per tree, total pollen per hermaphrodite flower, total pollen per inflorescence, and total pollen per tree for Reiek.	199-200
Table 5.17.	Spearman's rank correlation analysis between concentration of pollen grains and environmental parameters studied.	207
Table 5.18.	Types of sugars detected from the nectar of <i>P. timoriana</i>	218
Table 5.19.	List of amino acids detected from the nectar of <i>P. timoriana</i>	219
Table 5.20.	Spearman's rank correlation analysis between different nectar properties and environmental parameters studied.	222
Table 5.21.	Spearman's rank correlation analysis between nectar collected daily and environmental parameters studied.	223
Table 5.22.	Spearman's rank correlation analysis between concentration, time, sucrose, and hormones.	242
Table 5.23.	Spearman's rank correlation analysis between temperature, pollen germination and pollen tube length.	245

List of figures

Figure No.	Description	Page no.
Figure 3.1.	Geographical map of study site.	47
Figure 4.1.	Conceptual plot of the experimental design.	61
Figure 4.2.	The four-pollination treatments (Open, Closed, Day open, and Night open) of the experimental design.	62
Figure 5.1.	Reproductive phenological growth stages of <i>P. timoriana</i> as per BBCH scale.	76
Figure 5.2.	Reproductive phenological growth stages of <i>P. timoriana</i> as per BBCH scale.	77
Figure 5.3.	Types of <i>P. timoriana</i> flower: A= <i>P. timoriana</i> inflorescence, B= Hermaphrodite flower, C= Nectar producing flower, D= Staminoidal flower.	90
Figure 5.4.	The pattern of anthesis w.r.t. time block for the year 2021 and 2022.	90
Figure 5.5.	Different stages of anthesis of <i>P. timoriana</i> till fruits formation.	92
Figure 5.6.	The pattern of anther dehiscence w.r.t. time block for the year 2021 and 2022.	94
Figure 5.7.	a, b= anther dehiscence; c, d= longitudinal view of fully open anther; e, f= scanning electron micrograph image of fully open anther along with polyad pollen grains on the anther surface.	94
Figure 5.8.	The pattern of stigma receptivity w.r.t. time block for the year 2021 and 2022.	96
Figure 5.9.	Different stages of stigma receptivity. A-F= stigma receptivity test by using peroxidase-based hydrogen peroxide test. G-K= stigma receptivity test by using α -Naphthyl acetate as a substrate.	96
Figure 5.10.	Microphotographs of light microscopy showing pollen view and sculpturing of <i>P. timoriana</i> polyad pollen grains. Scale bars: A = 10X; B = 20X; C, D = 40X.	102
Figure 5.11.	Microphotographs of scanning electron microscopy showing pollen polar and equatorial view and sculpturing of <i>P. timoriana</i> polyad pollen grains. Scale bars: A= 220 μ m; B= 600 μ m; C, D= 1000 μ m; E= 5000 μ m; F= 7000 μ m.	102

Figure 5.12.	Pollinators of <i>P. timoriana</i> (A)	104
Figure 5.13.	Pollinators of <i>P. timoriana</i> (B)	105
Figure 5.14.	Random visitors of <i>P. timoriana</i>	106
Figure 5.15.	Visitation frequency of <i>Camponotus spp.</i> w.r.t. to time block for the year 2021 and 2022.	107
Figure 5.16.	Visitation frequency of <i>Tapinoma sessile</i> w.r.t. to time block for the year 2021 and 2022.	109
Figure 5.17.	Visitation frequency of <i>Bombus bicoloratus</i> w.r.t. to time block for the year 2021 and 2022.	111
Figure 5.18.	Visitation frequency of <i>Apis cerana indica</i> w.r.t. to time block for the year 2021 and 2022.	113
Figure 5.19.	Visitation frequency of <i>Trigona spp.</i> w.r.t. to time block for the year 2021 and 2022.	114
Figure 5.20.	Visitation frequency of <i>Vespa affinis</i> w.r.t. to time block for the year 2021 and 2022.	116
Figure 5.21.	Visitation frequency of <i>Phimenes flavopictus</i> w.r.t. to time block for the year 2021 and 2022.	118
Figure 5.22.	Visitation frequency of <i>Achaea serva</i> w.r.t. to time block for the year 2021 and 2022.	120
Figure 5.23.	Visitation frequency of <i>Agrotis infusa</i> w.r.t. to time block for the year 2021 and 2022.	122
Figure 5.24.	Visitation frequency of <i>Ercheia cyllaria</i> w.r.t. to time block for the year 2021 and 2022.	124
Figure 5.25.	Visitation frequency of <i>Eudocima phalonia</i> w.r.t. to time block for the year 2021 and 2022.	126
Figure 5.26.	Visitation frequency of <i>Hulodes caranea</i> w.r.t. to time block for the year 2021 and 2022.	127
Figure 5.27.	Visitation frequency of <i>Psyrassa unicolor</i> w.r.t. to time block for the year 2021 and 2022.	129
Figure 5.28.	Visitation frequency of <i>Ariadne merione</i> w.r.t. to time block for the year 2021 and 2022.	131
Figure 5.29.	Visitation frequency of bat w.r.t. to time block for the year 2021 and 2022.	133

Figure 5.30.	Visitation frequency of each pollinator for the year 2021 and 2022.	135
Figure 5.31.	Visitation frequency of each pollinator for the year 2021 and 2022 as per family wise.	137
Figure 5.32.	Visitation frequency of each pollinator for the year 2021 and 2022 as per order wise.	139
Figure 5.33.	Fruit formation % of autogamy, open pollination, geitonogamy, and xenogamy in 2021, 2022, and 2023.	154
Figure 5.34.	Effect of mating systems (autogamy, open pollination, geitonogamy, and xenogamy) on fruit formation in 2021, 2022, and 2023.	154
Figure 5.35.	A. Total no. of seeds per pod, B. Total no. of pods per capitulum, C. Seed lengths (mm), D. Weight of each seed (mg), and E. Seed diameter (mm) produced by each pollination treatment during the bagging experiment. Means are shown with bold number. The same letters are not significantly different from each other (Kruskal-Wallis test at the $p < 0.05$ level).	157
Figure 5.36.	No. of inflorescences per tree for three sites in 2021, 2022 and 2023.	160
Figure 5.37.	No. of flowers per inflorescence for three sites in 2021, 2022 and 2023.	160
Figure 5.38.	No. of nectar secreting flowers for three sites in 2021, 2022 and 2023.	163
Figure 5.39.	No. of hermaphrodite flowers for three sites in 2021, 2022 and 2023.	163
Figure 5.40.	No. of anthers per flower for three sites in 2021, 2022 and 2023.	166
Figure 5.41.	No. of pollen per anther for three sites in 2021, 2022 and 2023.	166
Figure 5.42.	No. of flowers per tree for three sites in 2021, 2022 and 2023.	168
Figure 5.43.	No. of nectar secreting flowers per tree for three sites in 2021, 2022 and 2023.	168
Figure 5.44.	No. of hermaphrodite flowers per tree for three sites in 2021, 2022 and 2023.	170
Figure 5.45.	No. of pollen per hermaphrodite flower for three sites in 2021, 2022 and 2023.	170

Figure 5.46.	No. of pollen per inflorescence for three sites in 2021, 2022 and 2023.	173
Figure 5.47.	No. of pollen per tree for three sites in 2021, 2022 and 2023.	173
Figure 5.48.	No. of ovules per flower for three sites in 2021, 2022 and 2023.	175
Figure 5.49.	Pollen ovule ratio for three sites in 2021, 2022 and 2023.	175
Figure 5.50.	No. of inflorescences per tree for three years in Sairang, Tanhril and Reiek.	178
Figure 5.51.	No. of flowers per inflorescence for three years in Sairang, Tanhril and Reiek.	178
Figure 5.52.	No. of nectar secreting flowers for three years in Sairang, Tanhril and Reiek.	180
Figure 5.53.	No. of hermaphrodite flowers for three years in Sairang, Tanhril and Reiek.	180
Figure 5.54.	No. of anther per flower for three years in Sairang, Tanhril and Reiek.	183
Figure 5.55.	No. of pollen per anther for three years in Sairang, Tanhril and Reiek.	183
Figure 5.56.	No. of flowers per tree for three years in Sairang, Tanhril and Reiek.	185
Figure 5.57.	No. of nectar secreting flowers per tree for three years in Sairang, Tanhril and Reiek.	185
Figure 5.58.	No. of hermaphrodite flowers per tree for three years in Sairang, Tanhril and Reiek.	188
Figure 5.59.	No. of pollen per hermaphrodite flower for three years in Sairang, Tanhril and Reiek.	188
Figure 5.60.	No. of pollen per inflorescence for three years in Sairang, Tanhril and Reiek.	190
Figure 5.61.	No. of pollen per tree for three years in Sairang, Tanhril and Reiek.	190
Figure 5.62.	No. of ovules per flower for three years in Sairang, Tanhril and Reiek.	193
Figure 5.63.	Pollen ovule ratio for three years in Sairang, Tanhril and Reiek.	193
Figure 5.64.	Pollen grain size and volume of <i>P. timoriana</i> .	202
Figure 5.65.	Concentration of pollen grains per cm ² for each time block.	204
Figure 5.66.	Concentration of pollen grains per m ³ for each time block.	205

Figure 5.67.	Pollen viability test by TTC	209
Figure 5.68.	Pollen viability test by FDA	209
Figure 5.69.	Pollen viability test by Alexander staining	209
Figure 5.70.	Comparison of pollen viability test by using TTC, FDA, and Alexander staining for hermaphrodite flower and nectar secreting flower.	210
Figure 5.71.	Comparison of pollen viability test between hermaphrodite flower and nectar secreting flower.	210
Figure 5.72.	Concentration (Brics) of nectar w.r.t. time	212
Figure 5.73.	Amount of nectar sugar (mg per µl) w.r.t. time block	212
Figure 5.74.	Amount of nectar collected (ml) in each time	215
Figure 5.75.	Nectar energetics value (J) w.r.t. time block	215
Figure 5.76.	Amount of nectar collected (ml) daily per inflorescence.	217
Figure 5.77.	Chromatogram of amino acids in nectar sample.	220
Figure 5.78.	Effect of distilled water and sucrose on <i>in vitro</i> pollen germination w.r.t. time block.	225
Figure 5.79.	<i>In vitro</i> pollen germination of <i>P. timoriana</i> pollen grains with extension of pollen tube.	225
Figure 5.80.	Effect of time on <i>in vitro</i> pollen germination w.r.t. distilled water and sucrose.	227
Figure 5.81.	Effect of distilled water and sucrose on <i>in vitro</i> pollen germination.	227
Figure 5.82.	Effect of time on <i>in vitro</i> pollen germination w.r.t. diff. conc. of IAA.	229
Figure 5.83.	Effect of diff. conc. of IAA on <i>in vitro</i> pollen germination w.r.t. time.	229
Figure 5.84.	Effect of time on <i>in vitro</i> pollen germination w.r.t. diff. conc. of IBA.	232
Figure 5.85.	Effect of diff. conc. of IBA on <i>in vitro</i> pollen germination w.r.t. time.	232
Figure 5.86.	Effect of time on <i>in vitro</i> pollen germination w.r.t. diff. conc. of K.	234
Figure 5.87.	Effect of diff. conc. of K on <i>in vitro</i> pollen germination w.r.t. time.	234

Figure 5.88.	Effect of time on <i>in vitro</i> pollen germination w.r.t. diff. conc. of GA.	237
Figure 5.89.	Effect of diff. conc. of GA on <i>in vitro</i> pollen germination w.r.t. time.	237
Figure 5.90.	Effect of diff. conc. of plant growth regulators on <i>in vitro</i> pollen germination.	239
Figure 5.91.	Effect of diff. plant growth regulators on <i>in vitro</i> pollen germination.	239
Figure 5.92.	Effect of temperature on <i>in vitro</i> pollen germination.	243
Figure 5.93.	Effect of temperature on pollen tube length.	243

List of abbreviations and symbols

Acronym/symbol	Full form/meaning
°C	Degree Celcius
%	Percentage
<,>	Less and greater than
'	Minutes
"	Seconds
µg	Microgram
&	And
°Bx	Degree Brix
AIC	Akaike information criterion
AM	Ante Meridiem
approx.	Approximately
BCCH	Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie
cm	Centimeter
cm ²	Square centimetre
DAB	Diamino benzidine
et al.	Co-workers
FCR	Fluorochromatic reaction
FDA	Fluorescein diacetate
E	East
GA ₃	Gibberellic Acid
etc.	And other similar things
HPLC	High performance liquid chromatography
hrs	hours
g	gram
IAA	Indole-3-Acetic Acid
IBA	Indole-3-Butyric Acid
H ₂ SO ₄	Sulphuric acid
(CH ₃ CO) ₂ O	Acetic anhydride
K	Kinetin
LM	Light microscopy
m ²	Square metre
m ³	Cubic metre
mg	Milligram
min	Minute
mg	Milligram
N	North
NTFP	Non-timber forest products
PAR	Photosynthetically active radiation
pH	Potential of hydrogen

PM	Post Meridiem
ppm	parts per million
PR	Precipitation
PS	Surface Pressure
QV	Specific Humidity at 2 Meters
RET	Rare, Endangered, and Threatened species
RH	Relative Humidity at 2 Meters
rpm	rotation per minute
RZSW	Root Zone Soil Wetness (surface to 100 cm below)
SEM	Scanning Electron Microscopy
ml	Millilitre
mm	Millimetre
spp.	Species
SR	Stigma receptivity
SSW	Surface Soil Wetness (surface to 5 cm below)
N	North
T	Time
TDEW	Dew/Frost Point at 2 Meters (C)
TM	Temperature at 2 Meters (C)
TMMA	Temperature at 2 Meters Maximum (C)
TMMI	Temperature at 2 Meters Minimum (C)
TTC	2,3,5-Triphenyl tetrazolium chloride
TWET	Wet Bulb Temperature at 2 Meters (C)
μl	Micro litre
μm	Micro metre
SD	Standard deviation
PGR	Plant growth regulator
±	Plus or minus

CHAPTER 1

INTRODUCTION

1.1. Impact of anthropogenic activities on tropical ecosystem reproductive dynamics

Tropical ecosystems, known for their remarkable biodiversity, play a fundamental role in sustaining global ecological processes, with a profound influence on plant reproductive biology (Sasaki *et al.*, 2024). These regions host a plethora of plant and animal species whose reproductive interactions are critical for the maintenance of biodiversity and ecosystem health. However, increasing human encroachment through deforestation, agriculture, and urbanization disrupts these ecosystems, leading to habitat loss and fragmentation. Such disturbances threaten the reproductive success of many plant species, mostly impacting pollination and seed dispersal mechanisms that perform on specific environmental interactions; this often shows compromised situations when their habitats are altered or diminished (Sodhi *et al.*, 2013).

One among the popularly profound impacts on tropical plant reproduction systems arises from excessive utilization of resources, exclusively targeting high-value plant species. Such exploitation narrows genetic diversity, weakening population resilience and stability (Alamgir, 2017). Disrupted reproductive cycles, particularly in species requiring specific pollinators, can destabilize plant-pollinator networks crucial for ecosystem functioning (Kaiser-Bunbury *et al.*, 2017). The removal of vital plant species triggers a domino effect across the ecosystem, affecting not that single species, rather on numerous animals that depend on them for sustenance and habitat, thus creating a ripple effect of biodiversity loss in the ecosystem (Sharma & Naik, 2024). Habitat fragmentation intensifies these reproductive challenges by isolating plant

populations, which reduces genetic exchange and impedes critical ecological processes like pollen and seed dispersal (Daele *et al.*, 2024).

Smaller, fragmented habitats often lack the resources to support viable populations, especially for species requiring large ranges for reproduction and dispersal (Lander *et al.*, 2019). This spatial isolation increases the risk of local extinctions, specifically in plants that depend on specific pollinators or animals for seed dispersal, further threatening the integrity of tropical ecosystems and their reproductive dynamics (Xiao *et al.*, 2016). The degradation of tropical ecosystems also influences directly on reproductive potential of plants tuned to specific ecological conditions (Sullivan *et al.*, 2024). For instance, many tropical plants rely on specialized animal pollinators or soil conditions that are lost when habitats are degraded. In such scenarios, reduced reproductive success diminishes the survival and regeneration of local plant populations, ultimately affecting the animals that depend on these plants, and leading to cascading effects that destabilize entire ecosystems (Mendes *et al.*, 2022). The broader implications of this include the loss of genetic diversity essential for adapting to environmental changes, thus weakening ecosystem resilience. Climate change further exacerbates these reproductive challenges by altering temperature and precipitation patterns, which can affect synchronic activity between flowering window and pollinator availability (Gérard *et al.*, 2020; Trunschke *et al.*, 2024). Such mismatches hinder reproductive success, increase the vulnerability of plant populations, and accelerate biodiversity loss (Kumar *et al.*, 2024). Conservation efforts are urgently needed to protect these fragile reproductive interactions and preserve tropical biodiversity.

1.2. Importance of reproductive interactions in plant ecology

Ecological interactions decide the reproductive success of many plant species, mostly targeting processes like pollination and seed dispersal. Pollination, often mediated by insects, birds, and mammals, are considered as a crucial process for genetic heterogeneity and population stability in many angiosperms under the continually changing climatic scenario. (Gamba & Muchhala, 2023; Gauzere *et al.*, 2020). Tropical ecosystems offer a complex and specialized mutualistic interaction between

existing flora and fauna. Many tropical plants have evolved specific traits to attract certain pollinators, *viz.*, vibrant colors, scents, and nectar rewards (Narayanan *et al.*, 2023). These adaptations facilitate effective pollen transfer and increase reproductive success (Ajani & Claßen-Bockhoff, 2021). However, habitat degradation and loss of pollinator populations threaten these mutualistic relationships, potentially leading to reproductive failure and population decline in plant species.

Plants that rely heavily on specific mutualistic interactions for reproduction are extremely vulnerable to environmental changes. For instance, the decline of a key pollinator species can significantly reduce the reproductive output of plants that rely on that fixed pollinator (Allen-Perkins *et al.*, 2024). This can lead to population declines and, in extreme cases, local extinctions. The extinction of a plant species directly affects other organisms within the ecosystem, as it removes a source of food or habitat for animals (Eichenwald *et al.*, 2024). In degraded environments, the absence of mutualistic partners can hinder the reproductive success of plants, as essential pollination services may be limited or completely absent (Moles *et al.*, 2022). Plants that fail to attract pollinators may experience reduced seed set and limited seedling recruitment, which can ultimately lead to population decline (Brown *et al.*, 2017). This lack of reproductive success underscores the significance of mutualistic interactions for the long-term survival of plant species (Moles *et al.*, 2022). Studies on plant reproductive ecology emphasize the need to understand the roles of pollinators in sustaining plant populations.

Research on endangered plant species has shown that their reproductive success is often compromised by the limited availability of pollinators (Thomann *et al.*, 2013). In such cases, conservation efforts must focus on preserving these interactions to ensure the existence of vulnerable plant populations (Christmas *et al.*, 2016). The fragmentation of habitats further complicates these ecological interactions by creating isolated patches of vegetation, where plant-pollinator and plant-disperser interactions are less frequent. Fragmented habitats are often less attractive to pollinators, which may prefer larger, contiguous areas with abundant resources (Teixido *et al.*, 2022; Steffan-Dewenter & Tscharntke, 1999). As a result, plants in fragmented habitats may

suffer from pollination limitations, which can hinder their ability to reproduce and maintain viable populations (Aguilar *et al.*, 2006). Human-induced changes, such as the introduction of invasive species, also impact mutualistic interactions (López-Vázquez *et al.*, 2024a). Invasive species can outpace native plants in attracting pollinators and dispersers, which lowers the reproductive success of native species (Cordero *et al.*, 2023). This competition can disrupt the balance of ecological interactions, further endangering native plants that depend on specific mutualists for survival (Aizen & Torres, 2024). Understanding the intricacies of reproductive interactions in tropical ecosystems is essential for conservation efforts (Monteiro *et al.*, 2024). By conserving and restoring these interactions, conservationists can help sustain plant populations and enhance the resilience of tropical ecosystems. This approach requires a comprehensive understanding of the specific ecological needs of both plants and their mutualistic partners, as well as the environmental factors that influence these interactions (Rafferty & Cosma, 2024).

1.3. Reproductive biology in conservation efforts

The reproductive biology of plant species is fundamental to their conservation, as it directly impacts their ability to maintain viable populations in the wild (Mabuza, 2024). For tropical plant species, understanding reproductive traits such as mating systems, pollination dynamics, and seed dispersal is essential for assessing their adaptability to environmental changes and potential for recovery (Rech *et al.*, 2018). These insights help conservationists identify specific challenges to reproduction and develop targeted oriented strategies to address them. In tropical regions, where biodiversity is rich and ecological interactions are complex, conservation efforts benefit greatly from a detailed understanding of reproductive biology (Silva *et al.*, 2024). For instance, knowledge of self-incompatibility mechanisms, floral morphology, and pollination requirements can guide restoration efforts by ensuring that plant populations have sufficient genetic diversity to thrive in fragmented habitats (Daele, 2024). Such strategies are critical in areas where habitat loss and fragmentation have isolated populations.

Conservation biology emphasizes the importance of maintaining genetic diversity within plants and across populations. This provides insights into genetic exchange mechanisms, including outcrossing and self-compatibility, which are vital for maintaining diversity within and among populations (Steinecke *et al.*, 2022). The conservation of mutualistic interactions, particularly those involving pollinators, decides the propagative nature of the tree (Ponce *et al.*, 2024; Quesada *et al.*, 2011). Conservation strategies that focus on conserving both plant and pollinator populations can help sustain these mutualistic relationships, thereby supporting long-term species survival. Species that are primarily outcrossing require a diverse genetic pool to avoid inbreeding depression. Understanding the breeding system of a species allows conservationists to predict how it will respond to habitat fragmentation and implement measures that promote genetic exchange, such as the establishment of wildlife corridors (Hilty *et al.*, 2019). Ex-situ conservation strategies, such as seed banks and botanical gardens, rely heavily on reproductive biology knowledge to maintain viable plant populations outside their natural habitats (Liu *et al.*, 2020). These efforts are crucial for preserving genetic material and ensuring the possibility of reintroducing species into the natural habitat if necessary. By studying the reproductive biology of endangered plants, conservationists can determine the best practices for seed storage, propagation, and reintroduction mechanisms (Maschinski & Albrecht, 2017).

1.4. Role of phenology in plant reproductive success

Studying phenology is crucial for understanding how well a tree species reproduces (Cerezini *et al.*, 2024). These events determine not only when plants can reproduce but also how effectively they attract mutualistic partners like pollinators and seed dispersers, which are essential for reproductive success. The precise timing of flowering is critical in tropical ecosystems, where competition for pollinators and dispersers is intense (Corlett, 2004). For instance, many tropical plants synchronize their flowering with the availability of specific pollinators, increasing the likelihood of successful pollination. However, even slight deviations in phenological timing due to environmental changes can lead to mismatches, where flowers bloom either too early or too late for their pollinators' activity periods, significantly affecting

reproductive success (Leclerc *et al.*, 2024). Research in tropical phenology often focuses on documenting these flowering and fruiting patterns across different populations and species.

Phenological studies provide insights into how plants adapt their reproductive strategies to seasonal cues and environmental conditions, which is essential for understanding the adaptive mechanisms that enhance species fitness in various habitats (Møller, 2023). Some plants may adjust their flowering times to avoid competition for pollinators, optimizing reproductive success through temporal isolation. Climate change presents a substantial risk to phenological synchrony in tropical ecosystems. For example, rise in temperatures may cause bolting, while pollinators may not adjust their activity periods accordingly. Such mismatches in phenology can lead to reduced pollination rates and a decline in seed production, ultimately affecting plant population viability (Leclerc *et al.*, 2024). Upon monitoring long-term phenological patterns, researchers can assess the resilience of plant species to shifting climates and identify those that are most vulnerable to phenological disruptions. This information is critical for conservation planning, as it allows for targeted efforts to protect species at risk of reproductive failure due to altered phenological cycles (Edwards *et al.*, 2024). In addition to flowering and fruiting, phenological research often examines leaf production and senescence. These processes are important for understanding the overall growth and development of tropical trees, as they are linked to nutrient cycling and energy allocation within the tree system (Ssali & Sheil, 2023). Leaf phenology influences photosynthetic rates, which in turn affect reproductive capacity and the ability to withstand environmental stressors (Chandarak *et al.*, 2023).

Another area of focus within phenology is the impact of biotic interactions on reproductive timing. By timing their flowering or fruiting to periods when herbivores are less active, plants can increase the chances of successful reproduction. These adaptive responses highlight the complex interplay between phenology, biotic interactions, and reproductive success (Rasmussen & Yang, 2023). The role of phenology in tropical ecosystems extends to the community level, where the timing of flowering and fruiting events influences species composition and ecosystem function.

In diverse tropical forests, overlapping flowering times create dynamic interactions among species, fostering competition as well as mutual support among plants with shared pollinators (Cleland & Wolkovich, 2024). Phenological studies at the community level help elucidate these interactions and provide a holistic understanding of ecosystem dynamics. Lastly, maintaining detailed, long-term phenological records is essential for monitoring the effects of climate change on tropical ecosystems. These records allow researchers to compare historical phenological data with current patterns, identifying shifts that may signal ecological disruption (Sathischandra, 2024).

1.5. Significance of breeding systems in plant reproduction

Breeding systems play a significant role in the reproductive success and genetic diversity of plant populations (Duan *et al.*, 2024). In tropical forests, where plant species often coexist in close proximity, breeding systems influence gene flow, reproductive isolation, and overall population resilience. The most common breeding systems in flowering plants are self-compatibility (allowing self-pollination) and self-incompatibility (requiring cross-pollination) (Kubota *et al.*, 2024). Understanding these systems as fundamental to conservation biology, in determining how plants will respond to habitat fragmentation, pollinator scarcity, and environmental changes. Self-incompatibility increases genetic diversity within populations, enhancing resilience to diseases, environmental stresses, and climate change (Thomas *et al.*, 2014). In contrast, self-fertile species are more adaptable to isolated conditions because they can reproduce even when mates or pollinators are scarce. This adaptability, however, often comes at the cost of reduced genetic diversity (Murúa *et al.*, 2020). The degree of self-incompatibility or self-compatibility in tropical plant species shapes how they respond to habitat fragmentation. For instance, species with strong self-incompatibility mechanisms are at greater risk in fragmented habitats, where limited access to compatible mates can reduce reproductive success and vice-versa (Ferrer *et al.*, 2024).

Conservation efforts must consider these breeding characteristics to maintain viable populations in fragmented landscapes, where the genetic diversity fostered by outcrossing is critical for long-term resilience. Tropical plant species exhibit a variety of breeding behaviors that reflect their evolutionary adaptations to specific

environmental conditions. Xenogamy, or obligate outcrossing, is prevalent among tropical plants and involves cross-pollination between different individuals. This system promotes genetic heterogeneity, which is crucial in diverse and competitive ecosystems like tropical forests. By facilitating gene flow, xenogamy enhances the capacity of populations to adapt to environmental challenges. Plants with complex floral structures and specialized pollination mechanisms are often associated with specific breeding systems that require cross-pollination. Such systems are found in many tropical species and contribute to the stability of plant-pollinator interactions within ecosystems. This co-evolutionary relationship underscores the importance of conserving both plant and pollinator species, as disruptions to one partner can compromise the reproductive success of the other (Tandon & Shivanna, 2020).

Self-fertilization, or autogamy, is another reproductive strategy that provides reproductive assurance under challenging conditions. This strategy is advantageous in environments where pollinators or mates are scarce, as it allows plants to produce offspring independently of external factors (Cheptou, 2019). However, autogamy often leads to inbreeding, which can reduce genetic diversity and increase susceptibility to environmental stresses. Plants in isolated or transient habitats may rely on autogamy for survival, but this strategy can limit long-term adaptability (Jacquemyn *et al.*, 2012). The reproductive assurance hypothesis suggests that plants with self-fertilization mechanisms are more likely to survive in extreme or unpredictable environments (Fenster & Marten-Rodriguez, 2007). Self-compatible plants, for instance, can maintain reproductive output in fragmented habitats where outcrossing is less feasible. However, the trade-off is that these plants may experience reduced genetic variability over time, which can limit their adaptability and resilience in the face of environmental changes (Rodger *et al.*, 2024). Understanding breeding systems is essential for designing effective conservation and restoration strategies, particularly for rare and endangered tropical species. Knowledge of whether a species is primarily outcrossing or selfing can help conservationists plan habitat restoration efforts, such as the reintroduction of pollinators or the establishment of mixed populations to encourage genetic exchange (Rodrigues *et al.*, 2019). Conservation

strategies that enhance genetic diversity within and among populations are vital for conserving adaptability and long-term survival of the species.

1.6. Role of floral biology in pollination success

Floral biology, encompassing flower structure, morphology, and reproductive organs, plays an essential role in pollination success and reproductive efficiency in tropical plants. The diversity in floral morphology, including variations in color, shape, scent, and nectar production, is often adapted to attract specific pollinators, thereby enhancing the likelihood of successful pollination (Rech *et al.*, 2018; Boulter *et al.*, 2009). This specialization is crucial in tropical ecosystems, where competition for pollinators can be intense due to high biodiversity. Flowers in tropical species exhibit a wide array of morphological adaptations aimed at attracting different pollinator types. For instance, bright colors and specific scents are commonly associated with flowers pollinated by birds and insects. Such traits are thought to evolve to attract pollinators that display floral constancy consistent visitation to flowers of the same species thereby maximizing pollen transfer efficiency. This floral specialization besides facilitating pollination also reduces interspecific competition, allowing diverse species to coexist within tropical ecosystems (Souza *et al.*, 2018).

Floral structure plays a crucial role in determining the pollination mechanism, whether by biotic agents like insects and birds or abiotic factors such as wind. The reproductive success of entomophilous plants largely depends on their ability to attract specific pollinators through specialized floral traits (Martínez-Gómez *et al.*, 2023). Conversely, anemophilous plants, which rely on pollen distribution through the air, often display simple floral structures designed to optimize pollen release and capture by neighbouring plants (Timerman & Barrett, 2021). In tropical forests, many flowering plants rely on intricate interactions with their pollinators. These mutualistic relationships are highly sensitive to changes in floral morphology (Martén-Rodríguez *et al.*, 2024). For example, plants with long floral tubes are often adapted to specific pollinators like hummingbirds or certain bees that can access nectar deep within the flower. This precise match between floral morphology and pollinator characteristics

helps ensure that only compatible pollinators, capable of effective pollen transfer, visit the flowers (Nunes *et al.*, 2016).

In tropical regions with distinct wet and dry seasons, many plants have evolved to flower synchronously to coincide with periods of optimal pollinator activity (Borchert *et al.*, 2004). This seasonal synchrony maximizes the chances of successful pollination by ensuring that flowers are available when pollinators are most abundant. Such adaptations underline the critical relationship between floral biology, environmental factors, and reproductive success (Bogdziewicz *et al.*, 2020). Floral dimorphism, a condition where plants produce morphologically distinct male and female flowers, also influences pollination success. Some tropical species exhibit dimorphism to attract a range of pollinators for both pollen and nectar resources, thereby increasing the likelihood of cross-pollination (Tsuji *et al.*, 2020). Dimorphism and other forms of floral polymorphism enhance the reproductive flexibility of plants, allowing them to adapt to varying pollinator availability and ecological conditions (Raju, 2019).

Floral biology extends beyond morphology to include the biochemical traits of flowers, such as nectar composition and scent production. These traits are crucial for attracting pollinators that rely on specific olfactory and gustatory cues to locate flowers. Nectar composition, for instance, varies across species and is often tailored to the nutritional requirements of particular pollinators. Understanding these biochemical aspects of floral biology is essential for grasping the ecological dynamics of pollination in tropical ecosystems (Vera & Pérez, 2024). Pollination success is not only a product of floral morphology and chemistry rather anthesis cycles significantly affect the process. Some tropical plants exhibit nyctinasty or thermonasty, which align with the activity patterns of nocturnal or crepuscular pollinators like bats and moths (Häder, 2019). These behavioral adaptations enhance pollination efficiency by ensuring that flowers are available to their primary pollinators at specific times of day or night. To conclude, research in floral biology is critical for conservation efforts, particularly for endangered species with specialized pollination systems. Conservationists can use knowledge of floral biology to design strategies that support pollinator populations, restore mutualistic interactions, and ensure the long-term reproductive success of

vulnerable plant species. This is particularly important in degraded habitats where natural pollination services are diminished, and artificial support may be necessary to maintain pollination success.

1.7. Pollination and its ecosystem impact

Pollination is a vital ecological process in any ecosystem, directly influencing the reproductive success and genetic diversity of angiosperms (Vinson *et al.*, 2018). Biotic pollination is the most common form of pollination in tropical regions, with approximately 90% of angiosperms relying on pollinators for reproduction (Quesada *et al.*, 2011). These pollinators ranging from insects to birds and mammals are crucial for maintaining healthy plant populations and ensuring ecosystem resilience. Tropical plants often exhibit specific floral traits that attract certain pollinators, such as bright colors, unique scents, and nectar rewards. These adaptations facilitate efficient pollen transfer by encouraging pollinator fidelity, where pollinators consistently visit the same species, maximizing the chances of successful fertilization (Patil *et al.*, 2023). However, habitat loss and fragmentation threaten these mutualistic relationships, as they reduce the availability of both plants and pollinators in tropical ecosystems (Ferreira *et al.*, 2020). Pollinator decline is a pressing issue in tropical regions, where human activities, including deforestation and pesticide use, have significantly reduced pollinator populations. These declines not only affect plant reproduction but also have broader ecological consequences, as plants that fail to reproduce cannot sustain populations of herbivores and other dependent species (Obregon *et al.*, 2021). The loss of pollinators is particularly detrimental to specialized plants that rely on a limited number of pollinator species for reproduction (Wandrag *et al.*, 2023).

The mutualistic relationship between plants and pollinators is often highly specific. Such specialization makes these plants more vulnerable to changes in pollinator availability, as the loss of a single pollinator species can lead to reproductive failure and population decline (Bergamo *et al.*, 2021). Hence, maintenance of pollinator diversity is an indispensable act in maintaining plant reproductive success in tropical ecosystems. The decline in pollinator populations also impacts genetic diversity within plant populations. Reduced pollination rates can limit gene flow between populations,

leading to genetic isolation and increased inbreeding. Inbreeding reduces genetic diversity, making populations more susceptible to environmental stresses, diseases, and climate change (Gamba & Muchhala, 2023). Consequently, pollinator conservation is crucial for sustaining not only individual plant species but also the genetic health of tropical plant communities (Katumo *et al.*, 2022). In degraded habitats, plants may face challenges in attracting pollinators due to a lack of floral resources or increased competition from invasive species. This competition can alter the behavior of pollinators, leading them to prefer more abundant or rewarding plants, thereby reducing the pollination success of native species.

Climate change is another factor that impacts pollination dynamics in tropical ecosystems (Kumar *et al.*, 2024). For instance, warmer temperatures may cause plants to flower earlier in the season, potentially before pollinators become active. Such phenological mismatches reduce pollination rates and hinder reproductive success, highlighting the need for climate-adaptive conservation strategies (Wang *et al.*, 2023). Pollination ensures the production of fruits, seeds, and plants, contributing to the stability of ecosystems and supporting agricultural yields (Kundu & Kumar, 2024). The loss of pollinators can therefore disrupt food chains and reduce the availability of essential resources in ecosystems. Protecting pollinator populations is thus integral to sustaining both biodiversity and ecosystem services that benefit humans and wildlife alike (Potts *et al.*, 2016). Understanding pollination biology is key to developing conservation strategies that support both plant and pollinator populations. Conservationists can implement measures such as creating pollinator-friendly habitats, reducing pesticide use, and restoring degraded areas to support pollinator populations (Joshi, 2024).

1.8. Pollen-pistil interaction and reproductive barriers

Pollen-pistil interactions represent a complex series of biochemical and morphological processes that play a critical role in plant reproduction. These interactions begin when pollen lands on the stigma of a compatible flower and involve multiple steps, including pollen adhesion, hydration, germination, and pollen tube growth through the style towards the ovule. Each stage of this process is influenced by specific biochemical

signals that ensure only compatible pollen successfully fertilizes the ovules, thereby promoting genetic diversity and reproductive success (Zhao *et al.*, 2023). The initial step of pollen-pistil interaction involves the recognition of compatible pollen by the stigma. This compatibility is determined by the biochemical properties of both the pollen and the stigma, which communicate through molecular signals; such a process is sensitive to environmental conditions (humidity and temperature) that can influence the rate of pollen germination (Edlund *et al.*, 2004). In self-incompatible species, these signals prevent self-pollen from germinating or reaching the ovule, promoting outcrossing and genetic diversity within populations (Nasrallah, 2024). This selective mechanism is particularly important in tropical forests, where high species diversity and close proximity of individuals increase the likelihood of encountering pollen from different individuals (Pontes *et al.*, 2024).

In tropical environments, where weather conditions fluctuate seasonally, plants may adapt their pollen-pistil interactions to align with periods of favorable environmental conditions, ensuring successful pollination and fertilization (Pacini & Dolferus, 2019). Following germination, pollen tube grows through style toward the ovule, guided by chemical gradients. This growth process is influenced by the structural and biochemical properties of the style, which may vary between species. For example, some plants have hollow styles that facilitate rapid pollen tube growth, while others have dense, solid styles that regulate pollen tube progression (Johnson *et al.*, 2019; Higashiyama & Takeuchi, 2015). These adaptations are crucial for managing pollen competition, as only the most viable pollen tubes reach the ovules. Reproductive barriers, including both pre- and post-fertilization mechanisms, play a vital role in maintaining species integrity in diverse tropical ecosystems (Leach, 2022). Pre-fertilization barriers, such as self-incompatibility and pollen-pistil incompatibility, prevent the fusion of incompatible gametes. Post-fertilization barriers, such as seed abortion or hybrid unviability, prevent the development of non-viable offspring (Zhong *et al.*, 2024). These barriers contribute to reproductive isolation, ensuring that gene flow occurs primarily within species and thereby maintaining species boundaries.

Self-incompatibility mechanisms prevent self-fertilization by recognizing self-pollen as incompatible, allowing only cross-pollination to proceed. This process is particularly important in tropical ecosystems, where the high density of conspecifics increases the likelihood of self-pollination (Bandeira e Sousa *et al.*, 2021). Self-incompatibility thus serves as a critical adaptation for maintaining genetic health and population viability. Partial incompatibility can also occur, where some level of self-fertilization is permitted, but cross-pollination is favored. This flexibility allows plants to maintain reproductive output even in low-pollinator conditions while still promoting genetic diversity (Tel-Zur, 2023). This balance between self- and cross-pollination, often observed in tropical trees, enable plants to reproduce in variable environmental conditions, supporting population resilience in fragmented or isolated habitats (Xiang *et al.*, 2022). Pollen-pistil interactions are also influenced by interspecific competition, especially in diverse ecosystems where multiple species may compete for the same pollinators. In such an environment, plants have evolved mechanisms to ensure pollen specificity, reducing the risk of hybridization and maintaining species integrity (Arceo-Gómez, 2021). These adaptations, including species-specific floral traits and pollen-pistil recognition systems, are essential for preserving biodiversity. The study of pollen-pistil interactions has significant implications for conservation, particularly for species that rely on specific pollinators or exhibit strong self-incompatibility. Understanding these reproductive mechanisms enables conservationists to implement targeted strategies that support natural fertilization processes, such as enhancing pollinator habitats or establishing mixed populations to promote genetic exchange. Such interventions are critical for preserving genetic diversity and ensuring reproductive success in threatened plant populations (Bashir *et al.*, 2024).

1.9. Factors influencing reproductive success

Reproductive success in tropical plants is shaped by a complex interplay of ecological, environmental, and biological factors (Barrett & Harder, 2017). These factors include pollinator availability, environmental conditions, floral morphology, breeding systems, and genetic diversity within populations. Together, they determine the reproductive output of plant species and influence population viability and adaptability

(Schoen *et al.*, 2019). Pollinator availability is a primary determinant of reproductive success in many tropical plants, as most species rely on biotic pollination for reproduction. The presence and behavior of pollinators directly affect pollen transfer and seed production, making pollinators an essential factor in the reproductive ecology of tropical plants (Bergamo *et al.*, 2021). However, habitat loss, climate change, and pesticide use can reduce pollinator populations, limiting reproductive success and hindering the regeneration of plant populations (Jacquemyn *et al.*, 2012). These factors affect the timing of flowering and fruiting events, which in turn determine the availability of floral resources for pollinators (Scaven & Rafferty, 2013). In tropical ecosystems, where temperature and precipitation patterns are often highly variable, plants must adapt their reproductive cycles to these conditions to maximize reproductive output (Shine & Brown, 2008).

Floral morphology and design also influence reproductive success by attracting specific pollinators and facilitating effective pollen transfer. The size, color, scent, and nectar rewards of flowers serve as cues for pollinators, encouraging repeated visits and enhancing pollination efficiency (Erickson *et al.*, 2022). Morphological adaptations in the form of large, brightly colored flowers to attract birds, while some emit specific scents to attract bees or bats ensuring pollination with minimal pollen wastage, thereby maximizing reproductive efficiency (Shivanna, 2023). Breeding systems, such as self-compatibility and self-incompatibility reproduce without and with external factors, respectively. Self-incompatibility ensures genetic diversity through cross pollination thereby increasing adaptability to environmental changes and habitat fragmentation yet may often struggle to reproduce in isolated populations where pollinators or compatible mates are inadequate (Ferrer *et al.*, 2024). Genetic diversity within populations is another critical factor affecting reproductive success. Conservation efforts that focus on maintaining genetic diversity within tropical plant populations can enhance reproductive success by reducing the risks associated with inbreeding depression and genetic bottlenecks (Lowe *et al.*, 2005). The density and spatial distribution of individuals within a population also impact reproductive success. In dense populations, the proximity of individuals facilitates pollen transfer, leading to higher seed set and greater reproductive success (Ghazoul, 2005). In contrast, sparse

or fragmented populations may experience pollination limitations, reducing reproductive output. Conservation strategies that promote habitat connectivity can help mitigate these challenges by allowing for greater genetic exchange and improving pollination rates (Bernhardt *et al.*, 2008).

Herbivory and predation are additional ecological factors that influence reproductive success in tropical plants. Herbivores may damage flowers, fruits, or seeds, reducing reproductive output of the species. Some plants have developed adaptive mechanisms, such as producing secondary metabolites or timing their flowering to avoid peak herbivore activity, to mitigate the impact of herbivory (McCall & Irwin, 2006). These adaptations are essential for maintaining reproductive success in environments where herbivores are abundant. Nutrient-rich soils support robust plant development, leading to greater reproductive potential (Carvalho *et al.*, 2021; Burkle & Irwin, 2009). Conversely, nutrient-poor soils may limit flowering and seed set, reducing reproductive success. Conservationists must consider these factors when designing habitat restoration projects, as ensuring appropriate soil conditions can enhance the reproductive success of reintroduced plant species (Smits, 2010). Finally, interspecific competition among plant species for resources such as light, water, and nutrients can affect reproductive success. In tropical forests, where biodiversity is high and competition is intense, plants have evolved various strategies to optimize resource use and maximize reproductive output. Understanding these competitive dynamics is important for conservation efforts, as it allows for the identification of factors that may limit the reproductive potential of endangered or rare species in multi-species environments (Wright, 2002; Coomes & Grubb, 2000).

1.10. Challenges in studying reproductive biology of trees

Unlike other plants, trees pose challenges in terms of size, long life cycles, and complex reproductive behaviours. Tropical trees, in particular, are often inaccessible for detailed observation and data collection, as many species grow to considerable heights and flower sporadically (Sasaki *et al.*, 2024) rendering difficulty in conducting comprehensive studies on their reproductive mechanisms. The seasonal nature of flowering in tropical trees further complicates research efforts. Many tree species

exhibit highly seasonal or unpredictable flowering patterns, which require long-term observation to capture accurate data. This seasonality is influenced by various environmental factors, including temperature, rainfall, and photoperiod, which are challenging to monitor consistently in tropical regions with limited research infrastructure (Datta *et al.*, 2024; Menon *et al.*, 2024). Shifts in temperature and precipitation patterns can alter the timing of flowering and fruiting, which may not align with the activity patterns of pollinators (Fleming *et al.*, 2024). This temporal mismatch can reduce reproductive success and compromise the resilience of plant populations in the face of environmental changes (Weir & Phillimore, 2024). Access to flowers for detailed study is another significant challenge. The height and canopy structure of tropical trees often make it difficult for researchers to reach flowers for sampling and observation.

In many cases, researchers rely on specialized equipment, such as climbing gear or drones, to access canopy-level flowers. These logistical challenges increase the time and cost associated with studying tree reproductive biology (Christiansen, 2023; Cannon *et al.*, 2021). Another challenge lies in the limited number of species that have been studied in depth. In India, detailed reproductive biology study has been conducted in only about 100 spp. among approx. 2,500 tree species (Tandon *et al.*, 2003). This limited research base constrains the understanding of reproductive traits across different species and ecosystems, hindering conservation efforts (Tiwari *et al.*, 2024). For instance, specific pollinators may only visit flowers at certain times or under particular environmental conditions, making it challenging to document all interactions accurately (Byers, 2017). Pollination studies are especially difficult for trees due to the unpredictable nature of pollinator visits (Ramírez & Kallarackal, 2018). Unlike plants that are close to the ground, tree flowers are less accessible to researchers, making it challenging to monitor pollinator behavior, pollen transfer, and pollination efficiency. This lack of data limits the understanding of how pollination affects reproductive success in tropical tree species (Moreira-Hernández & Muchhala, 2019). Moreover, the lengthy reproductive cycles of many tropical trees make it difficult to study their reproductive success over time (Sakai, 2001). Trees may only produce seeds once every few years, and growth and maturation of seedlings into

reproductive adults can take decades. Longitudinal studies are essential for understanding the full reproductive cycle, but they are resource-intensive and require sustained funding and commitment (Pesendorfer *et al.*, 2019). Finally, research on the reproductive biology of endangered tropical trees is limited, as many of these species are already at critically low population levels. Conducting studies on such small populations poses ethical and practical challenges, as sampling can further endanger the species. Conservation-focused reproductive studies must balance the need for data collection with the imperative to protect vulnerable populations (Holt *et al.*, 2014).

1.11. Threats to pollination systems

Human interventions create threats to tree pollination systems, which have led to declines in pollinator populations and disruptions in plant-pollinator interactions (López-Vázquez *et al.*, 2024b). Habitat loss, driven by deforestation and agricultural expansion, is one of the primary threats to pollination systems. When forests are cleared or fragmented, pollinators lose critical habitats, food sources, and nesting sites, leading to population declines and, in some cases, local extinctions (de Sousa *et al.*, 2022). Pesticides, particularly neonicotinoids, are known to have significant harmful effects on pollinators, impairing their foraging abilities, navigation, and reproductive health causing disruption in tree sexual propagation through proper pollination and fertilization processes (Obregon *et al.*, 2021). In addition to habitat loss and pesticide use, invasive species pose a significant threat to pollination systems (Solís-Montero *et al.*, 2023). Furthermore, invasive pollinators, such as certain species of bees, can disrupt existing pollination networks by monopolizing floral resources or introducing diseases to native pollinators, further threatening the stability of existing pollination systems (Simla *et al.*, 2022).

Climate change also has profound implications for pollination systems in tropical ecosystems. Understanding the impact of climatic factors on tree propagation enables conservationists to predict adaptive management strategies (Fugerey-Scarbel *et al.*, 2024). The loss of specialized pollinators is particularly concerning for tropical plants that have evolved highly specific relationships with certain pollinator species (Raiol *et al.*, 2021). For instance, some tropical orchids rely exclusively on particular species of

bees for pollination. The decline or extinction of these specialized pollinators can lead to reproductive failure and eventual population decline in these plants, highlighting the fragility of specialized pollination systems (Ackerman & Roubik, 2012).

In degraded habitats, the availability of floral resources may be insufficient to support healthy pollinator populations (Ghosh *et al.*, 2024). Plants in these areas may experience lower pollination rates due to reduced pollinator visitation, limiting their reproductive success. This scarcity of resources in degraded habitats highlights the need for habitat restoration efforts that include the re-establishment of native plant species to provide adequate food sources for pollinators (Kaiser-Bunbury, 2017). Pollinators' decline also affects food security and ecosystem services, as many tropical plants produce fruits and seeds that are essential for both wildlife and human communities. The decline in pollination services can reduce fruit and seed yields, impacting the availability of resources for the dependent beings (Katumo *et al.*, 2022). Additionally, the economic impact on local communities that rely on pollinated crops for income can be substantial. Effective conservation strategies for pollination systems require a multifaceted approach. This includes protecting pollinator habitats, reducing pesticide use, controlling invasive species, and promoting pollinator-friendly agricultural practices (Khan *et al.*, 2023a). Conservationists increasingly recognize the importance of community involvement in conservation initiatives, especially in regions where local populations depend on forest resources. Local communities often possess valuable knowledge of plant reproductive traits and ecological interactions, which can complement scientific research. By engaging communities in conservation efforts, programs can be more culturally relevant and sustainable (Cebrián-Piqueras *et al.*, 2020; Boillat *et al.*, 2013; Carvalho & Frazão-Moreira, 2011). For instance, policies that regulate the harvesting of endangered species can be based on data regarding flowering times, pollination needs, and seed dispersal mechanisms (Sharma *et al.*, 2022; Shivanna & Sanjappa, 2021). Effective policies require an evidence-based approach that considers the specific reproductive characteristics of each species, ensuring that conservation measures support both environmental and economic sustainability. Conservationists must also consider the impacts of climate change on pollination dynamics and implement adaptive management strategies to ensure the

resilience of pollination systems in tropical ecosystems. Public awareness and community involvement are crucial for the success of pollinator conservation initiatives. Educating local communities about the importance of pollinators and sustainable farming practices can help reduce pesticide use and encourage the protection of natural habitats. Engaging stakeholders at all levels, from farmers to policymakers, is essential for creating a supportive environment for pollinator conservation (Burns *et al.*, 2021). For this study, those trees which are grown in agroforestry system were selected as majority of this tree species was found growing in this system comparing with those of *P. timoriana* which are grown in forest or wild.

Considering the above mentioned facts and potential outcomes, this study was planned for *Parkia timoriana*, a culturally and ethnobotanically crucial tree species of the Indo-Burma hotspot region particularly in areas of Mizoram with the following broad objectives.

1.12. Objectives

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

CHAPTER 2

REVIEW OF LITERATURE

2.1. Role of plant reproductive biology in conservation

Reproductive biology involves the exploration of reproductive mechanisms and their interplay with both living organisms and non-living environmental factors. While the fundamental objective of reproduction in all organisms is to enhance reproductive success and genetic variability, the strategies employed to attain these outcomes vary among species. Some organisms, particularly plants, rely on external agents such as animals to facilitate specific reproductive functions. Many flowering plants adopt a dual reproductive strategy, utilizing both sexual reproduction via seeds and asexual reproduction through vegetative propagules. This combination maximizes reproductive fitness by integrating the benefits of both reproductive modes (Shivanna & Tandon, 2014).

Vegetative reproduction promotes the rapid lateral spread of populations, enabling colonization and local dominance in well-suited ecological niches. However, it restricts genetic diversity due to the absence of gene flow and the lack of dispersal advantages (Karunarathne *et al.*, 2018). Over time, increased homozygosity within the population can hinder long-term survival, as it diminishes the plant's ability to adapt to new environments, limiting its potential to colonize novel habitats and restricting populations to specialized ecological zones (Babynin *et al.*, 2023). Flowers serve as the reproductive organs in sexual reproduction. Thus, the initiation and development of flowers mark the first stage of sexual reproduction (Peterson, 2015). Sexual reproduction is unique in its capacity to enable genetic recombination through processes such as meiosis and fertilization, which leads to heritable variation and provides the foundational genetic material for evolutionary processes (Torre *et al.*,

2014). In comparison to other plant groups, sexual reproduction in flowering plants is more intricate and multifaceted (Peterson, 2015).

Wilcock & Neiland (2002) indicated that tropical rainforests are significantly threatened by reproductive failures, primarily due to limitations in pollination, seed dispersal, and the successful establishment of seedlings. In tropical regions, such as India, Indonesia, Malaysia, and Brazil, there is an increased risk of extinction at the population level for various tree species found within their forest ecosystems (Hooper *et al.*, 2012). Rapid declines in populations of threatened plant species in their natural environments are attributed to a range of anthropogenic activities (Panda *et al.*, 2018). A range of strategies and approaches, encompassing both in situ and ex situ conservation methods, have been suggested to protect plant resources. Nonetheless, these conservation strategies have not provided adequate protection for rare, endangered, and threatened (RET) tree species. Research on plant reproductive biology is crucial for various facets of biodiversity conservation, particularly in relation to reclamation and restoration efforts (Monika & Bhatnagar, 2007).

Reproduction is essential in determining the diversity and distribution of living organisms, with reproductive strategies affecting not only the quality and quantity of offspring but also the dynamics of genetic factors over time and space (Barrett, 2010; Charlesworth, 2006). Comprehensive knowledge of plant reproductive biology is essential for the conservation, management, and protection of endemic and endangered species (Spira, 2001; Evans *et al.*, 2003; Xiao & Xu, 2006). Investigating reproductive biology can also inform policies aimed at conserving rare species, which are vital for ecological restoration and reintroduction efforts (Monika & Bhatnagar, 2007). By examining the reproductive biology of rare, endangered, and threatened species, researchers can identify the underlying factors contributing to their rarity and develop scientific interventions to address these challenges (Ramasubbu *et al.*, 2011). Therefore, studies in reproductive biology are integral to effective conservation management strategies (Chen *et al.*, 2016).

Community-level investigations into the reproductive ecology of plants provide valuable insights for biodiversity management (Mittelbach & McGill, 2019; Kearns &

Inouye, 1997). Understanding biodiversity at the community level allows researchers to evaluate species interactions and ecosystem dynamics, thereby enabling more effective conservation strategies (Eisenhauer *et al.*, 2019). Additionally, integrating ecological characteristics of species with spatial patterns enhances our ability to predict and manage community responses to environmental changes (Mohebi & Mirzaei, 2021). Through research on reproductive biology, data regarding pollen banks, pollen viability, seed dormancy, and the longevity of seeds and seedlings across various plant species can be gathered (Monika & Bhatnagar, 2007). Additionally, these studies can elucidate patterns of genetic diversity, assess threats of loss, and evaluate the risks of inbreeding depression in relation to pollinator abundance (Evans *et al.*, 2003). Tandon *et al.* (2003) emphasized that research in reproductive biology is essential for conservation efforts, as it enhances our understanding of pollination processes and the limitations affecting fruit and seed development (Hamon *et al.*, 2024). Furthermore, studies focusing on reproductive biology can impact various wild populations. The success of reproduction plays a key role in determining population distribution through effective breeding systems, thus contributing to the maintenance of genetic diversity among different organisms (Rashid *et al.*, 2023).

Kwak & Bekker (2006) noted that reproductive biological data from various plant species have been utilized to assess the success rates and obstacles related to conservation efforts (Comizzoli & Holt, 2019). Although extensive resources are available to explore various aspects of reproductive biology in temperate species, information on tropical species is still limited (Rashid *et al.*, 2023). Furthermore, the reproductive biology of Indian plant species, particularly trees, has not garnered significant attention from researchers (Marbaniang *et al.*, 2018). Understanding plant reproductive biology could aid in evaluating adaptive significance and descriptive traits relevant to plant systematics. Furthermore, studies on plant reproductive biology are crucial for their conservation and management, as well as for the preservation of related animal species (Hamon *et al.*, 2024). Such studies contribute to the development of effective strategies for conserving the genetic diversity of various plant species and are critical for the restoration and rehabilitation of individual taxa

within their natural environments (Irudhyaraj & Ramasubbu, 2017; Paggi *et al.*, 2013; Tandon *et al.*, 2003; Raju & Rao, 2002).

2.2. Phenology of flowering plants: reproductive timing and environmental impacts

Phenology refers to the study of the somatic and generative phases, as well as periodic events in the natural life cycles of plants, including their sequential variations occurring within a defined timeframe (Morellato *et al.*, 2016; Nanda *et al.*, 2014; Williams-Linera & Meave, 2002). Studying the phenology of populations and communities is important for understanding the long-term adaptive strategies of species in response to prevailing environmental conditions, especially in terms of their reproductive success (Jerome *et al.*, 2021). Opler *et al.* (1980) emphasized that an understanding of phenological factors provides valuable insights for implementing effective management strategies for plant communities. Additionally, information regarding the phenophases of various organisms is essential for monitoring all environmental phases and is critical for comprehending the dynamic forces influencing different plant groups (Mohan *et al.*, 2019).

In flowering plants, phenological events, such as the initiation of flowering, fruiting, and seed dispersal, typically follow seasonal patterns. However, significant variation exists among species in terms of the timing, duration, intensity, and frequency of these events (Dorji *et al.*, 2013; Armstrong & Drummond, 1986). Annual fluctuations in these phenological events are often influenced by changes in environmental conditions, particularly factors such as rainfall, day length, and temperature (Keller & Shea, 2020). Additionally, phenological data collected across different latitudes, longitudes, and elevations can reveal general patterns in plant responses to these environmental variations (Shivanna & Tandon, 2014). Systematic and precise documentation of phenological events, along with corresponding climatic data, is essential for long-term monitoring of species' phenological responses to climate change (Inouye, 2008).

Phenological events related to flowering, such as the initiation of bud formation and the duration of peak flowering, can be influenced by the size and health of plant populations, as well as habitat quality (Elzinga *et al.*, 2007). Understanding phenophase events and the degree of asynchrony within individuals of the same species, as well as between species, can act as indicators for evaluating the impact of environmental stressors on plants (Kazan & Lyons, 2016). Examining phenological patterns within a specific environment can offer valuable insights into how climatic factors affect the success of developmental and reproductive processes in trees (de Carvalho *et al.*, 2015).

In India, there has been a greater focus on the phenological characteristics of various tree species in dry tropical forests compared to wet forests (Singh & Kushwaha, 2006; Singh & Singh, 1992; Prasad & Hegde, 1986; Kannan, 1994; Menon, 1993) and similarly there is only few studies done on the Indo Burma hotspot region of India compared with the other parts of India (Datta *et al.*, 2024). The peak bloom occurred between the second and third weeks of December. Fruiting commenced in the first week of January, overlapping with the later stages of flowering, and fruit maturation was completed in February, followed by dispersal in March and April. Khanduri & Kumar (2017b) noted that *Bombax ceiba* sheds its leaves during the flowering period, which occurs from the 2nd week of January to the 1st week of March. The fruiting phase persists for approximately 3 to 4 weeks, extending into April. Nayak & Davidar (2010) reported that the flowering periods for *C. brevispina*, *C. coromandelicum*, and *D. ovalifolia* were observed from February to April, while *E. bracteata* and *F. ramontchi* flowered in April, with fruiting occurring between May and June. The flowering and fruiting periods for *G. spicata*, *G. pentaphylla*, *I. pavetta*, and *L. tetraphylla* were noted from March to June.

Ramasubbu *et al.* (2011) investigated the reproductive biology of *Impatiens platyadena*, a critically endangered balsam species, noting that its flowering period occurs from September to December, with fruit maturation and dehiscence beginning in the 1st week of October. Storrs & Storrs (1990) reported the flowering phenology of *Elaeocarpus hygrophyllus* from March to May, with fruiting occurring between July

and September. For *E. lancifolius*, the flowering period extended from March to August, while the fruiting period was observed from October to December (Storrs & Storrs, 1990). Singh *et al.* (2016) examined the distribution status and various threats contributing to the population decline of several *Elaeocarpus* species across different forest regions in India, during which they assessed the phenological patterns. The flowering season of *E. acuminatus* was noted from July to September, with fruiting occurring between October and December. *E. amoenus* was found to flower from September to October, while its fruiting period was observed from March to April. Lastly, *E. floribundus* was documented to bloom from March to August, with fruiting observed between October and December.

Samy & Ramasubbu (2022) conducted a study on the floral characteristics and phenological patterns in relation to pollinator diversity among six selected endemic *Elaeocarpus* species in various forest regions of the Southern Western Ghats. Among the species investigated, the flowering periods for *Elaeocarpus* species were documented from May to September, with fruiting occurring from October to February. *E. gaussenii* exhibited its flowering season from April to June, while its fruiting period extended from June to October. Additionally, Sampaio *et al.* (2016) investigated the phenological behavior of *Adenocalymma nodosum* and *A. peregrinum* in the Brazilian Savanna, noting that the flowering season for *A. peregrinum* lasted from December to April, whereas *A. nodosum* flowered from March to June.

Tandon *et al.* (2003) conducted a study on the reproductive biology of *Butea monosperma*, noting that its flowering period occurred from February to April, while the fruiting period extended from March to May. Medan & Basilio (2001) investigated the reproductive biology of *Colleta spinossima* at six different locations in Argentina, where the flowering period was documented from July to September, and the fruiting period was observed from September to February. Choudhury *et al.* (2017) examined the floral phenology, flower-visitor interactions, and pollination processes of *Abrus precatorius*, finding that its flowering season lasted from August to October. Barman *et al.* (2018) explored the reproductive biology of *Salvadora oleoides*, where both flowering and fruiting were observed over a five-month period from January to May.

Chauhan (2015) investigated the phenology of *Litchi chinensis*, identifying the flowering period as occurring between February and April. Aswathi *et al.* (2018) studied the reproductive biology of Malabar tamarind (*Garcinia gummigutta*), where flowering was observed from March to April. Additionally, Ayyanar *et al.* (2021) studied the reproductive biology of East Indian stain wood (*Chloroxylon swietenia*), documenting its flowering period from February to August.

2.3. Impact of climatic variables on phenophase events

The reproductive phenology of plants is significantly influenced by various biotic and abiotic factors, including photoperiod, temperature, precipitation, and the activities of seasonal pollinators and seed dispersers, as well as their modes of dispersal (Morellato *et al.*, 2000; Pires *et al.*, 2018). The different phases of a plant's life cycle, including leaf emergence, flowering, pollination, fertilization, fruit development, seed dispersal, germination, and seedling survival, are all affected by climatic conditions (Woodward, 1987). Key climatic factors such as photoperiod, rainfall patterns, the duration of dry spells, temperature, water availability, and variations in day length have observable effects on various phenophases of plants (Prasad & Hedge, 1986; Bhat, 1992). Additionally, the observed differences in flowering phenology across years are likely shaped by climatic variables, including seasonal patterns, temperature fluctuations, water availability, and changes in photoperiod (Inouye *et al.*, 2003).

de Carvalho *et al.* (2015) investigated the interactions between phenological events and environmental factors, including temperature, rainfall, and photoperiod. Their findings revealed no significant correlation between leaf flush and environmental variables; however, leaf fall displayed a negative correlation with both temperature and rainfall. In contrast, the flowering period was positively correlated with temperature, whereas the fruiting period showed a positive association with both temperature and rainfall. Similarly, Nanda *et al.* (2013) investigated the relationship between leaf phenology in canopy tree species and rainfall and found a statistically significant negative correlation between leaf initiation and rainfall.

de Carvalho *et al.* (2015) reported that leaf initiation in the evergreen species generally occurs between October and April, during which a negative correlation with rainfall was observed in relation to leaf flushing. The leaf fall period was documented from January to July, with no significant association found between leaf fall and rainfall. During dry seasons, an increase in temperature, coupled with low humidity and declining soil moisture, has been associated with peak flowering in various plant species (Putz, 1979).

Kasi & Ramasubbu (2021) examined the relationship between climatic factors, specifically temperature and rainfall, and phenological events in the species *Elaeocarpus gaussenii* and *E. recurvatus* in the Southern Western Ghats. Their findings indicated a positive correlation between temperature and both leaf flushing and the flowering periods of these species, while a negative correlation was observed between leaf flushing and rainfall. Moreover, leaf fall displayed a positive correlation with both temperature and rainfall. Rainfall was also positively associated with the fruiting seasons of the studied species.

The Fournier Index serves as a valuable tool for the semi-quantitative assessment of phenophase intensity at both population and community levels across various plant species (Fournier, 1974). Utilizing the Fournier Index, Silva *et al.* (2014) documented the phenological patterns of tropical tree species, including *Balizia pedicellaris*, *Sloanea monosperma*, *Clethra scabra*, and *Cupania racemosa* in Brazil. Núñez-Cruz *et al.* (2018) studied that the reproductive phenology of eight tree species: *Bursera bipinnata*, *B. capallifera*, *B. fagaroides*, *B. globrifolia*, *Eysenhardtia polystachya*, *Leucaena macrophylla*, and *Guazuma ulmifolia* in the dry tropical forest of Mexico, where the fruiting intensity for each species was quantified using the Fournier Index. de Andrade *et al.* (2020) investigated the relationship between variations in temporal rainfall and phenological patterns in semiarid species in Brazil, employing the Fournier Index to measure the intensity of various phenological events, including leaf sprouting, flowering, and fruiting.

The integrated application of various indices can enhance the understanding of the impacts of phenological synchrony in plants (Freitas & Bolmgren, 2008). Data on

phenological events and the extent of asynchrony both within species and between species are crucial for assessing the effect of ecological disturbances on plant communities (Kushwaha & Singh, 2005). Flowering synchrony is essential for maintaining the conservation of genetic traits within populations and can also enhance genetic diversity among these populations. Augspurger (1983) investigated the flowering synchrony of six Neotropical shrub species and reported a synchrony index ranging from 0.48 to 0.89. Parra-Tabla & Vargas (2007) examined the flowering synchrony of *Myrmecophila christinae* over two years (1998 and 1999), with a synchrony index measured between 0.0025 and 0.03. For *Dianthus morisianus*, a flowering synchrony index of 0.81 ± 0.16 was documented (Nebot *et al.*, 2016). Piedrahita (2018) explored the relationship between flowering synchrony and floral display on the reproductive success of *Silene acaulis*, finding a positive correlation between the flowering synchrony index across different study years and fruit production.

2.4. Floral biology of plants

The life cycle of flowering species is typically divided into distinct stages, including germination, leaf unfolding, flowering, flower senescence, and leaf abscission (Lieth, 1974). However, the initiation and termination of these stages are influenced by environmental factors, and as a result, plants exhibit specific morphometric adaptations in response to these conditions (Kim *et al.*, 2011). Plants exhibit a diverse array of floral traits, which are associated with their adaptation to various pollinators (Johnson, 1996). The duration of flowering serves as a signal to attract pollinators, and a reduction in the length of the flowering period may limit the rate of visitation per flower (Arroyo *et al.*, 1981). In the case of *Colleta spinossima*, flowers typically opened in the morning, with a recorded floral longevity of 5 to 6 days; however, the anthers did not dehisce while in the bud stage (Medan & Basilio, 2001). Tandon *et al.* (2003) investigated the floral biology of *Butea monosperma*, noting that flowers opened between 09:00 and 10:30 AM, and typically withered after 1 to 2 days. *Moringa oleifera* exhibited an anthesis pattern from 6:00 AM to 12:00 PM, with anther dehiscence occurring between 07:00 AM and 01:00 PM (Bhattacharya & Mandal,

2004). *Shorea tumbergaia*, an endangered species from the Eastern Ghats, was observed to bloom at 08:00 AM, with anther dehiscence occurring approximately 2 hours after anthesis (Raju *et al.*, 2009). Shivanna (2009) studied the floral biology of *Adhatoda vasica* and recorded flower opening between 05:30 and 07:00 AM, with anther dehiscence noted at 09:30 AM, and flower longevity lasting up to 4 days.

Jacquemart *et al.* (2015) investigated the floral biology of *Impatiens balfourii* in France, noting that the flowers had a lifespan of up to 8 days. The flowering of *Saraca asoca* commenced between 03:00 and 05:30 AM, with anther dehiscence occurring simultaneously with anthesis (Smitha & Thondaiman, 2016). El Ottra *et al.* (2016) conducted floral biological studies on *Conchocarpus macrophyllus* in the Brazilian Atlantic forest, finding that *C. macrophyllus* exhibited a flower longevity of up to four days. Ramasubbu & Irudhyaraj (2016) recorded that *Elaeocarpus blascoi* flowers opened between 07:00 and 11:00 AM, with anthers beginning to dehisce 2 to 3 hours after anthesis.

Kumar *et al.* (2023) observed that in *Lagerstroemia speciosa*, anthesis occurred during the forenoon, between 05:00 and 11:00 hours, with peak flowering observed from 07:00 to 09:00 hours. In *Schima wallichii*, anthesis began at 06:00 hours, reaching its peak between 07:00 and 09:00 hours. As the day progressed, anthesis intensity diminished, reaching its lowest point at 11:00 hours, with a secondary peak in flower opening observed between 15:00 and 18:00 hours, indicating a bimodal anthesis pattern. Anther dehiscence occurred about one hour after anthesis, following a diurnal rhythm. Stigma receptivity began 4 hours after anther dehiscence and lasted for up to 60 hours. Choudhury *et al.* (2017) observed that the flowering of *Abrus precatorius* occurred in the early morning, with anthers beginning to dehisce asynchronously through longitudinal slits after anthesis. The flowers of *Curcuma aeruginosa* were noted to bloom between 06:30 and 07:30 AM, with anther dehiscence occurring from 07:30 to 08:30 AM, also through longitudinal slits (Aswani & Sabu, 2017). In *Gmelina arborea*, anthesis occurred between 06:00 and 11:00 hours. Anther dehiscence commenced approximately one hour after the onset of anthesis. Stigma receptivity coincided with the timing of anther dehiscence, and each flower remained receptive

for a duration of up to 18 hours. However, the maximum receptivity period was observed to last for approximately 12 hours (Khanduri *et al.*, 2019). Souza *et al.* (2017) investigated the floral biology of *Zeyheria tuberculosa*, reporting that flowers opened at 07:00 AM, with a lifespan of 2 to 3 days. For *Mesua ferrea*, flowering commenced between 04:00 and 05:00 PM, and anther dehiscence occurred one hour later via longitudinal slits (Kumar & Raju, 2021).

Anthesis and anther dehiscence are critical processes in flower development; however, during periods of rainfall, the timing of anthesis may be postponed. In natural ecosystems, a high abundance of pollinators has been associated with reduced flower longevity, as flowers tend to senesce more rapidly once the pollination process is complete (Nebot *et al.*, 2016). Extended flowering periods are known to attract a greater number of pollinators (Blionis *et al.*, 2001), thereby enhancing the rate of outcrossing. Furthermore, the longevity of flowers aids in the effective removal of pollen grains by various pollination agents (Giblin, 2005; Arroyo *et al.*, 2013).

Semerdjieva *et al.* (2023) indicated that the Scanning Electron Microscope (SEM) is an effective instrument for the examination of the reproductive structures in flowers. Ramasubbu & Irudhyaraj (2016) and Samy & Ramasubbu (2022) utilized SEM to study the morphology of the reproductive components, including the pistil, anther, and pollen grains, of several species. Additionally, Caceres *et al.* (2016) employed SEM to investigate the morphology of the pistil and pollen grains of *Olea europaea*, while Barbosa *et al.* (2018) examined the various parts of the pistillate and staminate flowers of *Philodendron propinquum* using SEM.

2.5. Floral volatiles and nectar as pollinator attractants

Floral volatiles play a crucial role in attracting pollinators and serve as indicators that guide floral visitors to the rewards offered by flowers (Knudsen & Gershenzon, 2006). However, these volatile compounds can negatively impact plant communities by attracting inefficient pollinators, nectar thieves, and herbivores (Miyake & Yahara, 1999). The use of neutral-red stain confirmed that osmophores are responsible for the sweet scent emitted by the flowers of *Conchocarpus macrophyllus* (El Ottra *et al.*,

2016). Additionally, Veni & Richard (2018) investigated the floral morpho-anatomy of *Atlantia monophylla* and identified the presence of osmophores responsible for the fragrance of the flowers, as demonstrated by the neutral-red staining technique.

Nectar is recognized as the most prevalent reward for biotic pollination in the flowers of angiosperms (Nicolson & Thornburg, 2007). It is hypothesized that nectar is composed primarily of a concentrated sugar solution (Pacini & Nepi, 2007). Nicolson & Thornburg (2007) noted that the composition of nectar is further enriched by the presence of alkaloids, proteins, free amino acids, vitamins, metal ions, oils, and pigments. The levels of nectar produced are influenced by several intrinsic plant characteristics, such as genetic factors, the age of the flower or plant, herbivore damage, and diseases caused by various organisms. Additionally, environmental conditions, including temperature, relative humidity, and water availability, significantly affect nectar production (Pacini & Nepi, 2007).

The concentration of nectar solutions is a critical factor in the energetics of foraging behavior (Heinrich, 1975). Various characteristics of nectar, including daily production rates, sugar concentration, and diurnal variation, are fundamental to the associations between pollinators and plants (Baker, 1975). Microcapillary tubes and refractometers are commonly utilized to measure the volume and sugar concentration of floral nectars (Corbet, 2003). For instance, *Petrocoptis grandiflora* was found to produce an average of 0.5 ± 0.3 μl of nectar, with a sugar concentration recorded at $41.4 \pm 10.1\%$ (Navarro *et al.*, 1993). In another study, *Cerinthe major* exhibited a nectar volume of 1.34 ± 0.73 μl (Nocentini *et al.*, 2012). Sampaio *et al.* (2016) reported a nectar volume of 33 μl with a sugar concentration of 22% in *Adenocalymma nodosum*. Additionally, *Zeyheria tuberculosa* produced an average of 1.6 ± 0.3 μl of nectar, which had a sugar concentration of $19.7 \pm 2.9\%$ (Souza *et al.*, 2017).

The volume and concn. of nectar in flowers significantly influence the behavior of floral visitors and the interactions between plants and animals (Baker, 1975; Galetto & Bernardello, 2005). Plants with nectar concentrations ranging from 15% to 25% are conducive to butterfly pollination (Proctor *et al.*, 1996), while flowers with nectar concentrations between 21% and 46% are more likely to attract bee pollinators (Baker

& Baker, 1982; Opler, 1983). Bees exhibit a strong preference for flowers that contain a small quantity of nectar with a high sucrose concentration (Jacquemart *et al.*, 2015; Nicolson & Thornburg, 2007; Petanidou *et al.*, 2000). Conversely, bats and birds tend to favor flowers that offer a larger volume of nectar with lower sugar concentrations (Baker & Baker, 1983). Numerous studies have indicated that alkaloids and phenolic compounds can also serve as attractive cues for various pollinators (Adler & Irwin, 2005; Irwin *et al.*, 2004). Furthermore, nectar thieves, such as skipper butterflies and ants, are influenced by iridoid glycosides, including catapult and catalposide.

2.6. Pollen biology in flowering plants

Assessing pollen quality is crucial for the effective storage of pollen grains, understanding pollen-pistil interactions, and conducting studies on incompatibility and fertility (Shivanna & Rangaswamy, 1992). Insufficient or dysfunctional pollen production can pose significant barriers to fertilization in plants. For example, *Butea monosperma* was found to produce an average of $5,382 \pm 340.76$ pollen grains from nine united stamens, while a single flower yielded $52,775.49 \pm 1,698.03$ pollen grains (Tandon *et al.*, 2003). *Elaeocarpus blascoi* produced an average of $50,700 \pm 456$ pollen grains per anther and $1,368,900 \pm 2,680$ pollen grains per flower (Ramasubbu & Irudhyaraj, 2016; Irudhyaraj, 2016). Renjumol & Radhamany (2017) studied the pollen biology of *Amherstia nobilis*, observing that a single anther produced an average of $9,659.66 \pm 124.62$ pollen grains, resulting in $86,759 \pm 447.77$ pollen grains per flower. In *Solanum torvum*, an average of $30,500 \pm 8,524$ pollen grains per anther and between 158,620 and 192,620 pollen grains per flower were recorded (Saha & Datta, 2017). *Monoon tirunelveliense* exhibited an average of 750 ± 60 pollen grains per anther, with a total of $165,000 \pm 100$ pollen grains per flower (Viswanathan *et al.*, 2019).

Generally, pollen grains are characterized by various shapes, including spherical, elliptical, triangular, quadrangular, rectangular, and rhombic forms (Shivanna & Tandon, 2014). Ueda & Tomita (1989) identified six primary types of pollen grains and three subtypes of exine sculpture within the genus *Rosa*. The family Boraginaceae is noted for having the smallest pollen grains, approximately 5 μm in diameter, while

Cymbopetalum odoratissimum (Annonaceae) has been reported to produce the largest pollen grains, measuring up to 350 μm (Walker, 1971). Ramasubbu & Irudhyaraj (2016) examined the pollen biology of *Elaeocarpus blascoi*, noting that the tricolporate pollen grains measured between 10 and 12 μm in size.

2.7. Pollen-ovule ratio of plants

It has been suggested that in angiosperms, the pollen-to-ovule (P:O) ratio plays a crucial role in determining the plant's breeding system, with higher P:O ratios increasing the likelihood of outcrossing (Khanduri *et al.*, 2015a). Similarly, Michalski & Durka (2009) found a significant correlation between the P:O ratio and the outcrossing rate, concluding that the P:O ratio is a more reliable indicator of the pollination mode than the mating system itself. Navarro *et al.* (1993) investigated the reproductive biology of *Petrocoptis grandiflora* in the Northwest Iberian Peninsula, reporting a pollen-ovule ratio of 641.4 ± 89.6 . For *Colleta spinossima*, a pollen-ovule ratio of 7433:1 was documented (Medan & Basilio, 2001). In the case of *Saraca asoca*, the pollen-ovule ratio was recorded at 1808.92:1 (Smitha & Thondaiman, 2016). Ramasubbu & Irudhyaraj (2016) calculated the pollen-ovule ratio for *Elaeocarpus blascoi* as 57,031:1. Samy & Ramasubbu (2022) examined the pollen-ovule ratios of several *Elaeocarpus* species from the Southern Western Ghats, including *E. gaussenii*, *E. recurvatus*, *E. serratus*, *E. tuberculatus*, and *E. variabilis*. Choudhury *et al.* (2017) reported a pollen-ovule ratio of 342:1 for *Abrus precatorius*. Additionally, Viswanathan *et al.* (2019) recorded the pollen-ovule ratio of *Monoon tirunelveliense* as 6,600:1.

2.8. Techniques for assessing pollen viability in plants

Pollen viability, which is indicative of male fertility, is commonly assessed to evaluate the fertility of stored pollen grains and to promote cross-fertilization between different genotypes of flowering plants (Oliveira *et al.*, 2001). Analyzing pollen viability is beneficial in understanding the breeding systems of various plant species (Stone *et al.*, 1995). Pollen viability is crucial for plant hybridization, with viability tests ranging from just a few minutes in self-pollinated species to several hours or even days in

cross-pollinated species (Jayaprakash, 2018). Low pollen viability can result in insufficient pollination, thereby threatening the reproductive success of individual plant species, particularly in small and isolated populations (Ottaviano & Mulcahy, 1989). Pollen viability tests employing staining techniques have been used to assess enzymatic activity, membrane integrity, and the stability of the nucleus and cytoplasm within pollen grains (Nepi & Franchi, 2000; Shivanna & Rangaswamy, 1992; Vizintin & Bohanec, 2004). Generally, chemical staining methods enable the differentiation of viable pollen grains from non-viable ones, making them widely applicable in various areas of plant science. These staining techniques are typically faster and simpler than *in-vitro* and *in-vivo* germination methods (Barrow, 1981). Several staining agents, including Alexander stain, Aniline blue, Acetocarmine, TTC, MTT, Lactophenol cotton blue, and X-Gal, have been utilized to analyze pollen grain viability (Khatun & Flowers, 1995).

In Alexander stain technique, the protoplasm of the pollen grains is stained with acid fuchsin, while cellulose is stained with malachite green. Pollen grains that appear dark purple are classified as viable, whereas those that are green are deemed non-viable (Peterson *et al.*, 2010). Bhattacharya (2004) investigated the pollen viability of *Anacardium occidentale*, reporting that $76.2 \pm 2.10\%$ of the pollen grains were viable. In a study conducted in Perugia, Italy, the pollen grains of *Cupressus arizonica* were collected in 1994 and 2000 and subsequently stained with Alexander's stain, yielding a viability rate of approximately 94.1% to 94.7% across both years (Ariano *et al.*, 2006). Moraes *et al.* (2009) examined pollen viability of *Hypericum brasiliense* using Alexander stain, finding that 83.5% of pollen grains from normal anthers were viable. In another study, Coelho *et al.* (2012) reported a pollen viability range of 45.34% to 99.34% among ten different accessions of *Crotalaria juncea*. The analysis of *Litchi chinensis* pollen grains with Alexander's stain revealed that $78 \pm 14\%$ of the grains were viable (Chauhan, 2015). Furthermore, the pollen viability rates for *Aechmea bicolor*, *Alcantarea nahoumii*, *Pseudananas sagenarius*, and *Vriesea carinata* were observed to be 90.33%, 70.33%, 97.67%, and 87.76%, respectively (Souza *et al.*, 2017). Oliveira *et al.* (2019) assessed the pollen viability of *Passiflora edulis* using

Alexander stain, recording $32,136 \pm 3,183$ pollen grains as viable, while Buchner *et al.* (2022) reported a viability rate of 95% for *Fraxinus excelsior*.

The acetocarmine staining technique is effective in revealing the presence of cytoplasm within pollen grains, with viable pollen staining pink to deep red, while non-viable pollen grains remain unstained, appearing transparent or white (Marutani *et al.*, 1993). Shaina & Beevy (2015) investigated the reproductive biology of *Coccinia grandis*, using the acetocarmine test to determine pollen viability, which revealed that 89.98% to 97.91% of the pollen grains were fertile. In a study by Sampaio *et al.* (2016), the pollen fertility of *Adenocalymma nodosum* and *A. peregrinum* was found to be 95.5%. The pollen viability of *Elaeocarpus blascoi* was recorded at 59.4%, with a gradual decline observed thereafter (Irudhyaraj, 2016). For *Zeyheria tuberculosa*, the pollen fertility was measured at $86 \pm 17.2\%$ (Souza *et al.*, 2017). In *Eleutherine bulbosa*, the recorded pollen fertility was $74.76 \pm 5.66\%$ (Manjula & Nair, 2018). In the case of *Salvadora oleoides*, fresh pollen grains showed a fertility rate of $95.4 \pm 1.58\%$ when assessed using the acetocarmine test (Barman *et al.*, 2018). The pollen grains of *Garcinia gummi-gutta* exhibited a fertility rate of $94.1 \pm 0.66\%$ on the day of anthesis, followed by a gradual decrease in fertility (Aswathi *et al.*, 2018). Additionally, Buchner *et al.* (2022) reported a viability rate of 97% for pollen grains in *Fraxinus excelsior*.

In this TTC test, living pollen tissue metabolizes the TTC, converting a colorless compound into a colored one, known as formazan, through the reduction process facilitated by the enzyme dehydrogenases (Nortin, 1966; Beyhan & Serdar, 2008). This test is regarded as a reliable measure of viability across various taxa (Shivanna & Johri, 1989). Ramasubbu *et al.* (2011) reported a pollen viability rate of 74% in *Impatiens platyadena*. In *Elaeocarpus blascoi*, pollen viability was recorded at 54.2% on the day of anthesis, declining to 11.7% after four days (Irudhyaraj, 2016). Saha & Datta (2017) investigated the reproductive biology of *Solanum torvum* in Northeast India, finding that the TTC test indicated a pollen viability of $63.20 \pm 4.28\%$. For *Salvadora oleoides*, pollen viability was measured at $64.12 \pm 3.12\%$, which decreased to $46.66 \pm 2.54\%$ after three days (Barman *et al.*, 2018). Chauhan (2019) conducted a

pollen viability test on *Saraca asoca* using a 1% TTC solution, reporting a viability of 51.34% at anthesis, while *Monoon tirunelveliense* exhibited a viability range of 60.3% to 72.9% (Viswanathan *et al.*, 2019).

The fluorescent diacetate test is commonly employed to assess pollen grain viability (Sharma *et al.*, 2010). The fluorochromatic reaction (FCR) test is recognized as a rapid and straightforward method that facilitates pollen germination and enables sperm cells to reach the embryo sac (Shivanna *et al.*, 1991). Fluorescein diacetate releases fluorescein when pollen grains possess cytoplasmic esterases in their plasma membranes. Viable pollen grains contain cytoplasmic esterases, while non-viable pollen grains lack these enzymes (Shivanna & Tandon, 2014). Tandon *et al.* (2003) reported that no pollen viability was detected in *Butea monosperma* when the pollen grains were analyzed using fluorescein diacetate.

Ramasubbu *et al.* (2011) conducted reproductive biological studies on *Impatiens platyadena*, utilizing the fluorochromatic reaction (FCR) test, which indicated that 75% of the pollen grains were viable on the day of anthesis. In a study on *Impatiens balfourii*, Jacquemart *et al.* (2015) found that $98 \pm 1\%$ of the pollen grains were viable when assessed with fluorescein diacetate. Smitha & Thondaiman (2016) reported a pollen viability of 51.34% in *Saraca asoca* at anthesis, with a gradual decline in viability observed after 4 to 6 hours, ultimately resulting in no viable grains. For *Elaeocarpus blascoi*, the viability was recorded at 52.6% on the day of anthesis, decreasing to 9.2% after 4 days (Irudhyaraj, 2016). Renjumol & Radhamany (2017) found that $29 \pm 5\%$ of pollen grains in *Amherstia nobilis* were viable, while *Monoon tirunelveliense* exhibited a viability range of 62.2% to 80.6% across different populations (Viswanathan *et al.*, 2019). Ayyanar *et al.* (2021) reported that in *Chloroxylon swietenia*, the viability of pollen grains ranged from 38% to 66% when assessed using the FCR test.

Maues *et al.* (2008) evaluated the pollen viability of *Jacaranda copaia* using the Diamino Benzidine (DAB) test at various time intervals, finding that the highest viability (75.5%) occurred between 08:00 AM and 09:00 AM, with a subsequent gradual decline in viability. In the case of *Impatiens platyadena*, Ramasubbu *et al.*

(2011) reported that 73% of pollen grains were viable, while *Elaeocarpus blascoi* exhibited a viability rate of 78.2% on the day of anthesis. Irudhyaraj (2016) recorded a pollen viability of 54.4% at anthesis for *Hopea ponga*, with a gradual decrease in viability observed thereafter. Abdelgadir *et al.* (2012) investigated the pollen viability of *Jatropha curcas* using the Potassium Iodide test, reporting that $97.0 \pm 1.5\%$ of pollen grains were viable at anthesis. Additionally, the Iodine Potassium Iodide test was employed to assess viability in various *Momordica species*, where 89.68% to 94.19% of pollen grains were recorded as viable at anthesis, followed by a gradual decrease in viability (Rathod *et al.*, 2018).

2.9. *In vitro* pollen germination techniques in plants

The viability of pollen grains can be evaluated using both *in vitro* and *in vivo* germination methods (Alcaraz *et al.*, 2011; Acar & Kakani, 2010; Dafni, 1992; Manjula & Nair, 2018; Shivanna & Rangaswamy, 1992). The *in vitro* pollen germination method is noted for being less time-consuming and is particularly beneficial for studies related to plant breeding (Rodriguez-Riano & Dafni, 2000; Satish & Ravikumar, 2010). Factors such as genetic background, environmental conditions, pollen grain maturity, as well as the composition and pH of the germination medium significantly influence *in vitro* pollen germination outcomes (Rathod *et al.*, 2018).

Jayaprakash & Sarla (2001) indicated that pollen can be germinated in various media, with the composition of these media varying among different species. Linskens (1967) utilized a combination of sucrose and boric acid to facilitate pollen germination, while other media were enhanced with polyethylene glycol and various amino acids (Shivanna *et al.*, 1997). In this context, sugar serves as an osmotic regulator, facilitating water movement from the medium into the pollen grains through diffusion. In *in vitro* studies on litchi, a germination rate of 66% was observed using a medium containing 24% sucrose and agar (Mustard *et al.*, 1953). Similarly, research on *Coccinia grandis* indicated that pollen germination increased with higher sucrose concentrations, peaking at 35%. Germination rates rose steadily from 5% to 35% sucrose concentration, followed by a decline at 50% concentration (Shaina & Beevy, 2015). In studies of *Amherstia nobilis*, pollen grains were subjected to Brewbaker and

Kwack's medium with varying sucrose concentrations (5-50%), with the highest germination rate observed at 35% sucrose (Renjumol & Radhamany, 2017). Ayyanar *et al.* (2021) conducted *in vivo* pollen germination studies on *Chloroxylon swietenia* using different sucrose concentrations (20-100%), finding that a concentration of 60% sucrose yielded the highest pollen germination rate.

2.10. Stigma receptivity and its role in plant fertilization

The pistil is recognized as the female reproductive structure in flowering plants and serves as the recipient of pollen grains, exhibiting various morphological characteristics (Heslop-Harrison, 1987). Notably, in protogynous species, stigma receptivity occurs prior to anther dehiscence, while in protandrous species, receptivity may be observed after the anthers have dehisced (Shivanna & Tandon, 2014). The surface of the receptive stigma contains extracellular proteins, which may be present as a pellicle in dry stigmas or as exudates in wet stigmas. Important components of the receptive stigma's surface include esterase and peroxidase (Dafni & Maues, 1998; Bhattacharya & Mandal, 2004; Sreekala *et al.*, 2008). Numerous studies have indicated that the surface of receptive stigmas contains biochemical compounds such as amino acids, carbohydrates, lipids, proteins, and phenolic compounds (Shivanna, 2003).

The stigma receptivity period of *Anacardium occidentale* was observed to occur between 8:00 AM and 8:00 PM (Bhattacharya, 2004). In *Moringa oleifera*, receptivity lasted for up to four days, with the highest pollen germination rate of 48.47% recorded on the third day after anthesis (Bhattacharya & Mandal, 2004). Ramasubbu *et al.* (2011) examined the stigma receptivity of *Impatiens platyadena*, noting that the stigma remained wet and non-papillate, and was receptive for up to three days post-anthesis. *Impatiens balfourii* exhibited a maximum receptive period of eight days (Jacquemart, 2015). The stigma of *Litchi chinensis* was found to be receptive for three hours, from 9:00 AM to 12:00 PM, extending up to two days (Chauhan, 2015). In *Elaeocarpus* species, a dry and papillate type of stigma was observed, with receptivity recorded between three and seven days (Ramasubbu & Irudhyaraj, 2016; Samy & Ramasubbu, 2022). Manikandan (2016) investigated the reproductive biology of *Garcinia imberti*

and *G. travancorica*, observing that the female and bisexual flowers maintained receptivity for up to eight days after anthesis.

Souza *et al.* (2017) conducted floral biological studies on *Zeyheria tuberculosa*, analyzing stigma receptivity using the hydrogen peroxide test, which indicated that the stigma remained receptive for up to two days following anthesis. In *Abrus precatorius*, the stigma was noted to be wet and papillate, with peak receptivity observed three hours after anthesis. Additionally, the highest *in vivo* pollen germination rate of 75.29% was recorded at this time (Renjumol & Radhamany, 2017). Barman *et al.* (2018) examined the floral biological characteristics and stigma receptivity of *Salvadora oleoides*, noting that maximum receptivity occurred one day prior to anthesis, with a wet-papillate stigma documented. The plant retained its receptivity for three days thereafter. Jothish & Anilkumar (2019) investigated the stigma receptivity of *Cassine kedarnathii* in the Western Ghats, finding that the stigma remained receptive for up to 20 hours after anthesis.

2.11. Pollination ecology: roles of animal pollinators in plant reproduction

In angiosperms, successful pollination is essential for fertilization and seed development, relying on mutualistic relationships between plants and various animal pollinators, including bees, butterflies, moths, beetles, bats, ants, flies, birds, and snails (Jennersten, 1988). Pollinators are crucial for the transfer of pollen among flowers within a species and between different flowering plants. Ollerton *et al.* (2011) indicated that approximately 90% of angiosperms are pollinated by animals, while the remaining 10% rely on abiotic factors for pollination. Among animal pollinators, insects are the most significant contributors (Renner & Ricklefs, 1995; Linder, 1998; Friedman & Barrett, 2009). Additionally, some species exhibit autogamy, particularly through cleistogamous and chasmogamous forms of pollination (Kaul & Koul, 2009). In tropical forests, the majority of plants are primarily pollinated by insects, which are regarded as obligate outcrossers (Bawa, 1990).

Certain animals are classified as specialist pollinators, as they have adapted to feed on the floral resources of specific plant species, while others are considered generalist

pollinators, utilizing resources from a broader array of flowering plant species (Waser *et al.*, 1996). To attract these pollinators, plants must offer various rewards, including pollen, nectar, and edible oils (Herrera & Pellmyr, 2002). Additionally, some flowers provide shelter for pollinators, allowing them to rest or seek refuge during adverse weather conditions, such as wind and rain (Gumprecht, 1977). Floral traits, including shape, size, and abundance, significantly influence visitation rates and subsequent fruit and seed set. The frequency of floral visitors is impacted by flower shape (Gomez *et al.*, 2008), and larger flower sizes are often positively correlated with increased visitation rates (Bell, 1985; Eckhart, 1991).

It has been observed that a majority of dioecious plants achieve seed production primarily through cross-pollination (Richards, 1997), with an estimated 63% of fruit or seed production lost due to a shortage of pollinators (Ratto *et al.*, 2018). In recent years, tropical rainforests have experienced significant biodiversity loss attributed to habitat destruction and climate change, which has placed biotic pollinators in increasingly vulnerable positions (Tylianakis, 2013). The availability of floral rewards can influence pollinator behavior by increasing visitation frequency or enhancing pollination quality, ultimately contributing to the success of plant reproductive processes (Pang *et al.*, 2012). Specific colors have been linked to particular functional groups of pollinators, with these functional groups often being emphasized in pollination biology rather than individual floral visitors (Muchhala *et al.*, 2014). Reverte *et al.* (2016) noted that while pollinators may show preferences for certain colors, similarly colored flowers do not necessarily attract the same pollinators. This phenomenon is attributed to the chromatic vision of pollinators. Floral color also influences the visitation patterns of insect pollinators; for instance, hummingbirds are attracted to red flowers, bees favor blue flowers, and beetles are more likely to visit white or creamy-colored flowers (Waser *et al.*, 1996). Additionally, flying foxes and birds have been identified as foragers on the flowers of certain *Elaeocarpus* species (Russ, 1999).

Short floral tubes and pink corollas featuring nectar guides are characteristic adaptations for bee pollination (Endress, 1994; Proctor *et al.*, 1996). Additionally, bees

utilize these structures to forage for nectar and pollen (Kevan, 2005). *Apis dorsata* has been identified as a floral visitor of *Butea monosperma* (Tandon *et al.*, 2003). In various species of *Persoonia*, *Apis mellifera* was observed foraging with the highest abundance of individuals (Rymer *et al.*, 2005). Nayak & Davidar (2010) investigated the pollination biology of several species, where they recorded *Apis dorsata*, *A. cerana*, and *A. florea* as effective pollinators for different plant species, with visitation frequencies ranging from 7.2% to 12.8%. Furthermore, *Apis mellifera* and various *Bombus* species were noted as floral visitors to *Cerithe major* (Nocentini *et al.*, 2012).

Ogilvie & Thomson (2015) investigated the pollination biology of *Gentiana parryi*, documenting five different bumblebee species: *Bombus balteatus*, *B. appositus*, *B. flavifrons*, *B. californicus*, and *B. sylvicola*. In their study, *Elaeocarpus* species were observed with *Apis cerana indica*, *Apis dorsata*, and *A. mellifera*, with visitation frequencies ranging from 2.0 to 5.12 (Samy & Ramasubbu, 2022). *Apis dorsata* was identified as the most frequent floral visitor to *Saraca asoca* (Smitha & Thondaiman, 2016). In *Psydrax dicoccos*, several pollinators were recorded, including *Amegilla sp.*, *Apis dorsata*, *A. indica*, *Thyreus sp.*, *Lasioglossum sp.*, and *Trigona sp.*, with visitation frequencies ranging from 0.51 to 11.16 (Subha & Richard, 2016). The flowers of *Syzygium caryophyllatum* were visited by *Apis cerana indica*, *A. dorsata*, and *A. florea*, which were effective pollinators (Geethika & Sabu, 2017). Additionally, the flowers of *Santalum album* were noted to attract *A. cerana* (Krishnakumar *et al.*, 2018).

Flies are commonly observed floral visitors, recorded in approximately 1,100 plant species across 172 families (Kearns, 2001). Bruckman & Campbell (2014) studied pollinator assemblages in *Phacelia parryi*, identifying *Allograpta spp.*, *Bombylius spp.*, *Copestylum spp.*, *Eupeodes sp.*, *Sphaerophoria sp.*, and several unidentified syrphid flies, with visitation frequencies ranging from 0.03 to 2.08. *Colocasiomyia* flies were observed visiting *Schismatoglottis baangogensis*, with peak activity occurring between 6:20 AM and 7:20 AM, during which they fed on the stigmatic fluid of the flowers (Hoe & Wong, 2016). *Melagyna sp.* and *Eristalinus megacephalus* were

recorded as floral visitors to *Psydrax dicoccos*, with visitation frequencies ranging from 0.51 to 2.85 (Subha & Richard, 2016). In *Elaeocarpus* species, visitors included *Lucilia sericata*, two unidentified flies, *Drosophila melanogaster*, and *Calliphora vomitoria* (Samy & Ramasubbu, 2022). Lau *et al.* (2016) conducted studies on the pollination biology of *Goniothalamus tapisoides* and *G. longistipites*, finding *Drosophila melanogaster* to be an effective pollinator. Similarly, Aswani & Sabu (2017) observed *Drosophila melanogaster* in *Curcuma aeruginosa*.

Flowers that bloom during the day and possess sweet fragrances along with long, slender floral tubes are adapted for butterfly pollination (Dobson, 2006; Shivanna & Tandon, 2014). Butterflies are active visitors to *Impatiens* flowers during daylight hours, their activity is significantly reduced on rainy days (Ramasubbu *et al.*, 2011). *Eugenia discifera*, a tropical semi-evergreen tree, has also been observed to attract butterflies at various times (Rajkumar *et al.*, 2015). Several butterfly species, including *Heliconius sara-apsedes*, *Heliconius melpomene-nanna*, *Oleria aquata*, and *Eurema albula*, have been identified as floral visitors to *Conchocarpus macrophyllus* (El Ottra *et al.*, 2016). Additionally, *Anaphaeis aurota* (Pioneer/Capper white), *Pachliopta hector* (Crimson rose), *Ratinda amor* (Monkey puzzle), *Euploea core* (Common crow), *Castalius rosimon* (White zebra), and *Junonia lemonias* (Lemon pansy) were recorded as pollinators of *Psydrax dicoccos*, with visitation frequencies ranging from 0.77 to 4.93 (Subha & Richard, 2016). Floral visitors to *Syzygium caryophyllatum* included *Hamadryas amphinome*, *Euploea core*, *Junonia iphita*, *Junonia lemonias*, and *Catopsila sp.* (Nadarajan & Pujari, 2019). Furthermore, butterflies such as *Hypolimnas bolina* and *Junonia iphita* were noted as floral visitors to *Elaeocarpus gaussenii* and *E. variabilis*, with their visitation frequencies measured between 1.07 and 1.19 (Samy & Ramasubbu, 2022).

In addition to butterflies, nocturnal pollinators such as bats and moths have been documented in various tropical and subtropical plant species (Endress, 1994; Gibson, 2001). Flowers that are characterized by long, narrow tubes and white corollas often emit a strong, sweet fragrance at night and exhibit predominantly nocturnal anthesis, traits that are typical of moth-pollinated flowers (Proctor *et al.*, 1996). The trees of

Psydrax dicoccos were visited by different species of *Macroglossum*, with visitation frequencies ranging from 0.25 to 4.41 (Subha & Richard, 2016). In the case of *Elaeocarpus* species, visits were recorded from *Xanthopan morganii* and unidentified moth species, with their visitation frequencies calculated to be between 0.65 and 1.23 (Samy & Ramasubbu, 2022).

Beetles are recognized as floral visitors primarily to larger flowers that possess a non-specialized structure, often bowl-shaped or cylindrical, with exposed reproductive organs. These flowers typically lack nectar guides, exhibit dull coloration, emit strong odors, and provide easily accessible rewards (Listabarth, 2001). Beetle pollination has been documented in various plant families, including *Palmae* (Henderson, 1986), *Nymphaeaceae* (Prance, 1980), and *Annonales* (Armstrong & Drummond, 1986). In the case of *Elaeocarpus* species, two unidentified beetle species were noted as floral visitors, with their visitation frequencies ranging from 1.33 to 5.6 (Samy & Ramasubbu, 2022). Hummingbirds, sunbirds, sugarbirds, honeyeaters, and honeycreepers have been reported as effective pollinators for various plant species (Kearns & Inouye, 1993). In India, 58 bird species have been identified as pollinators for 93 species of angiosperm plants (Subramanya & Radhamani, 1993).

Albano *et al.* (2009) investigated the diversity of pollinators in strawberry fields in Portugal, analyzing the activity rates, visitation frequencies, and visitation rate indices for various pollinator groups. The active rates for honey bees, flies, beetles, and butterflies ranged from 0.1 to 7.45, while the visitation rate indices were recorded between 0.67 and 50. Pollination efficiency was assessed by identifying the quantity and placement of pollen grains on the bodies of visitors, as well as through careful observation or cinematography of their foraging behavior (Macior, 1967).

2.12. Plant breeding systems and their role in pollination and seed production

Understanding various plant breeding systems is crucial for identifying seed production mechanisms associated with different pollinators, as well as for elucidating gene flow dynamics among distinct plant populations (Dafni, 1992). The reproductive success of plants, and consequently their population abundance, is likely influenced,

at least in part, by their breeding systems (Rymer *et al.*, 2005). Furthermore, breeding systems play a significant role in guiding conservation efforts within diverse plant communities (van Diggelen *et al.*, 2001) and are critical in determining the degree of fruit set (Richards, 1997). Generally, breeding systems are shaped by various floral traits, including flower size and shape, floral display, the extent of dichogamy, self-incompatibility mechanisms, and the overall architecture of flowers on plant branches (Harder & Barrett, 1996; Richards, 1997).

Plants that rely on animal pollination typically enhance outcrossing by effectively displaying their flowers and providing floral rewards to attract pollinators (Fisogni *et al.*, 2011). Self-incompatible and xenogamous species tend to produce a greater quantity of pollen grains (Baker, 1967; Cruden, 1973). In their breeding study on *Butea monosperma*, Tandon *et al.* (2003) reported a maximum fruit set of 22.51% resulting from xenogamy, while apomixis and spontaneous autogamy did not lead to fruit set. Research on the breeding systems of *Eugenia discifera* revealed that the species supported open pollination, autogamy, geitonogamy, and xenogamy, but no fruit set was observed in apomixis (Rajkumar *et al.*, 2015). Irudhyaraj & Ramasubbu (2017) conducted various breeding experiments on *Elaeocarpus blascoi*, which also supported open pollination, autogamy, geitonogamy, and xenogamy, recording a maximum fruit set of 84% through geitonogamous pollination. Nadarajan & Pujari (2019) documented a fruit production rate of 42% in *Syzygium caryophyllatum*, achieved primarily through xenogamous mechanisms, while other systems, such as autogamy and geitonogamy, did not facilitate fruit set. In contrast, *Salvadora oleoides* successfully produced fruit under autogamous, xenogamous, and open pollination systems (Barman *et al.*, 2018). Chauhan (2019) examined the breeding system of *Saraca asoca*, finding that open pollination led to a higher fruit set percentage of 7.5%, with geitonogamous and xenogamous systems also contributing significantly to fruit production.

CHAPTER 3

STUDY SITE

The research titled “Reproductive biology of *Parkia timoriana* (DC.) Merr. under the silvihorticultural system in Mizoram, North-East India” was conducted over a period from 2021 to 2024. The study was carried out in the regions of Tanhril, Sairang, and Reiek, located in the state of Mizoram, India (Figure 3.1.).

3.1. Mizoram

3.1.1. Geographical location

Mizoram is located in the northeastern part of India, with international borders bordering Myanmar to the east and Bangladesh to the west and south. To the north, it is bordered by the Indian states of Assam and Manipur, while Tripura lies to the west. The Tropic of Cancer also crosses through the state of Mizoram. Mizoram is a part of the "Seven Sisters" of northeastern India, a region known for its distinctive topography, characterized by mountain ranges, valleys, and lush forests. Geographically, the state is located between latitudes 21°58' N to 24°35' N and longitudes 92°15' E to 93°29' E, making it a landlocked state nestled in the northeastern corner of India.

The terrain of Mizoram is predominantly hilly, occupying a land area of 21,087 square kilometers, and is part of the Indo Burma hotspot region of the world. These rugged hills and valleys are a defining feature of the state's landscape and are responsible for its rich biodiversity (Mishra *et al.*, 2021). Mizoram is home to several major rivers, including the Tlawng, Tut, Tian, Tuichawng, Tuirial, Tuipui, Tuivawl, Teirei, Tuirini and Serlui, which flow through the hills, contributing to its diverse hydrological system

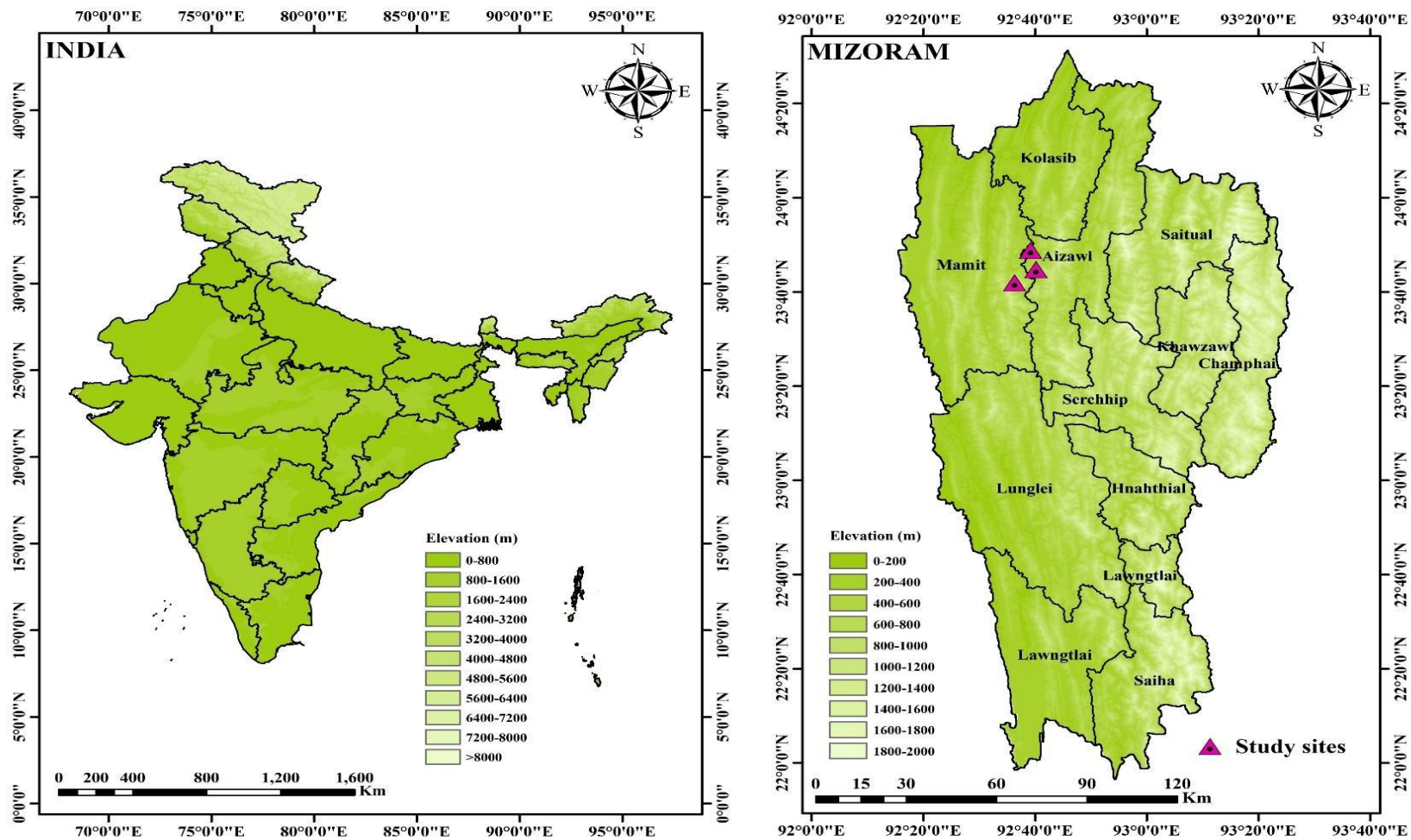


Figure 3.1. Geographical map of study site

(Verma, 2024). The state's geographical features position it within the Indo-Burma biodiversity hotspot, highlighting its ecological significance. Mizoram's climate is classified as subtropical highland, characterized by heavy rainfall during the monsoon season and mild winters. The region's location in the rain shadow of the Himalayas results in relatively high precipitation, contributing to its abundant vegetation and diverse ecosystems.

3.1.2. Climate

The climate of Mizoram is primarily influenced by its geographical location within the eastern Himalayas, resulting in a subtropical highland climate. The state experiences distinct wet and dry seasons, with the monsoon period characterized by heavy rainfall and moderate temperatures throughout the year. The region's climate is classified as a tropical monsoon with cooler highland features, owing to its mountainous terrain (Saitluanga *et al.*, 2021). The monsoon season, from May to September, is marked by intense rainfall, primarily driven by southwest monsoon winds. During this period, rainfall can exceed 2,500 mm annually in some areas, supporting the region's dense green cover and contributing to its biodiversity. The wet season is also characterized by high humidity levels, which can surpass 80% during peak rainfall months (Muniyan & Lallawmzuali, 2024).

In contrast, the dry season from October to April sees reduced rainfall and relatively moderate temperatures. The temperature during this period typically ranges between 20°C and 30°C during the day, with cooler nights, particularly in the higher altitudes, where temperatures can dip between 10°C and 15°C (Lalrinmawia, 2024). Winter, from December to February, brings cooler conditions, especially in the northern and southern hills, where frost conditions can occur at higher elevations. Despite these cooler conditions, the climate remains temperate compared to other northern regions of India. Mizoram's climate, with its varied elevation and proximity to the Bay of Bengal, supports a rich biodiversity, making it one of India's most ecologically diverse regions.

3.1.3. Characteristics of the soil

The soils of Mizoram are primarily composed of red and lateritic types, characteristic of tropical and hilly regions (Dolui & Mondal, 2007). These soils are rich in iron and aluminum oxides, which impart a reddish color and contribute to their acidic nature. The high acidity of the soils influences the vegetation types that can be supported, often limiting the range of crops and plant species (Brajendra & Sarma, 2016). The organic content in Mizoram's soil is high due to the dense vegetation and humid climate that facilitates the rapid decomposition of plant matter. This organic richness supports the growth of a variety of crops, such as rice, maize, and vegetables, which are crucial to the state's agricultural activities. However, despite their fertility, these soils are prone to erosion, particularly in the hilly regions, due to the steep slopes and intense monsoon rains, which exacerbate soil loss.

In terms of fertility, Mizoram's soils often lack essential nutrients such as nitrogen, which are leached away due to the heavy rainfall. To counteract this, farmers use organic fertilizers and compost to replenish the soil's nutrient content. The traditional practice of shifting cultivation (jhum) in the hilly areas involves clearing forested land for cultivation and allowing it to regenerate over time, which helps maintain soil fertility (Grogan *et al.*, 2012). The soils in the lower elevation areas tend to have more clay and loamy textures, which improve their moisture retention, making them suitable for crops that require more water. However, the risk of waterlogging during the monsoon season, especially in compacted areas, can negatively affect crop growth. The soil pH typically ranges from 4.5 to 6.0, further limiting the types of crops that can be grown without soil amendments. Mizoram's soils, while naturally fertile, face challenges from erosion and nutrient deficiencies (Brajendra & Sarma, 2016). Sustainable soil management practices, including the use of organic farming techniques, are essential to maintaining their productivity and mitigating the impacts of soil degradation.

3.1.4. Vegetation and forest

Mizoram's vegetation is largely shaped by its geographical features, with the state hosting a variety of tropical, subtropical, and temperate forest types, each

corresponding to different altitude, rainfall, and temperature zones. The state is highly forested, with around 90% of its land area covered by forests, making it one of the most densely forested states in India (Sati & Vangchhia, 2016). These forests are essential not only for biodiversity but also for maintaining the ecological balance of the region. Mizoram's tropical forests are home to a variety of tree species, such as *Castanopsis tribuloides*, *Schima wallichii*, and *Aporosa octandra*. Other significant species found in the region include *Artocarpus*, *Syzygium*, *Michelia*, and *Terminalia*. At higher altitudes, temperate forests are primarily composed of species like *rhododendron*, which flourish in the cooler temperatures.

In addition to their biological significance, Mizoram's forests also provide NTFPs such as bamboo, rattan, and medicinal plants. Bamboo is particularly important in Mizoram's economy, used in construction, handicrafts, and as food (Vanlalruati *et al.*, 2024). The forests also support a wide range of wildlife, including endangered species like the *Nycticebus coucang*, *Capricornis rubidus*, *Nemorhaedus goral*, *Panthera tigris*, *Panthera pardus*, *Neofelis nebulosi*, *Prionailurus bengalensis*, and *Ursus thibetanus*, *Helarctos malayanus*, which are protected within these ecosystems. Despite the ecological value of Mizoram's forests, the practice of shifting cultivation (jhum) has led to deforestation and degradation in some areas, raising concerns about biodiversity loss. Efforts to implement sustainable farming practices, such as agroforestry and reforestation, are crucial for mitigating these impacts and preserving the state's rich natural heritage.

3.1.5. Agriculture

Agriculture is a cornerstone of Mizoram's economy, with a large proportion of the rural population relying on farming for their livelihood. The state's agriculture is shaped by its mountainous terrain, tropical climate, and forested landscapes, which determine the cultivation methods and crop patterns (Grogan *et al.*, 2012). Shifting cultivation (jhum) has traditionally been the dominant agricultural practice, although modern, sustainable farming practices are increasingly being adopted to address the environmental challenges posed by this method. Traditional jhum cultivation is practiced in the hilly areas, where rice and other crops such as maize, beans, and sweet

potatoes are grown (Swami, 2018). The state also practices permanent farming in terraced fields, especially for rice cultivation, and is known for producing varieties like bamboo rice and glutinous rice, which are integral to the local diet.

In addition to food crops, Mizoram also grows a range of horticultural crops, including fruits like oranges, pineapples, and guavas, and vegetables such as cabbage, tomatoes, and cauliflower. The region's high rainfall during the monsoon season supports the growth of these crops, particularly where irrigation infrastructure is in place. The state also produces spices such as ginger and turmeric. Organic farming, which avoids synthetic chemicals, is well-suited to Mizoram's hilly terrain, where the fragile soils can benefit from these practices. However, agriculture in Mizoram faces challenges such as soil erosion, reliance on monsoon rainfall, and the impacts of climate change. Sustainable land management practices, such as agroforestry and watershed management, are being implemented to address these issues and improve the resilience of the agricultural sector (Grogan *et al.*, 2012).

3.1.6. Agroforestry

Agroforestry in Mizoram is a crucial practice that combines trees with agricultural systems to enhance productivity, promote sustainability, and conserve the environment. The state's distinct topography, climate, and soil conditions make agroforestry an integral component of its agricultural framework. This practice addresses challenges such as soil erosion, land degradation, and biodiversity loss, while also providing socio-economic benefits to rural communities (Saha *et al.*, 2010). Historically, Mizoram's farming practices have been centered on shifting cultivation, or jhum, a system that clears forested land for farming, followed by a fallow period for soil regeneration. However, concerns over soil degradation and deforestation have led to the adoption of more sustainable agroforestry methods. Agroforestry now integrates tree planting with crop cultivation on the same land, improving soil fertility, enhancing water retention, and providing supplementary income (Saha *et al.*, 2010).

In lower altitudes and terraced fields, common agroforestry species include fruit trees such as banana, orange, and guava, alongside timber species like teak and pine. The practice of agroforestry with perennial crops, particularly in hilly regions, helps reduce

reliance on shifting cultivation (Choudhury *et al.*, 2022). It mitigates soil erosion by providing ground cover and protecting topsoil during monsoons. Tree roots stabilize the soil and retain moisture, which is particularly beneficial during dry spells. Organic matter from decaying plants contributes to soil fertility, vital in nutrient-poor soils. Agroforestry systems also NTFPs, further diversifying income sources. Support from government and non-governmental organizations has helped promote agroforestry through training, incentives, and organic farming practices. However, challenges such as limited resources, knowledge, and land tenure issues hinder widespread adoption. Despite this, agroforestry remains a promising solution for enhancing Mizoram's agricultural resilience.

3.1.7. Demography

Mizoram's demographic profile is shaped by its geographical, cultural, and historical contexts. As of the 2011 Census, the population of Mizoram is approximately 1.1 million, with a population density of 52 individuals per square kilometer, lower than the national average. The population distribution is influenced by the state's mountainous terrain, with settlements concentrated in valleys and plains due to the difficult topography. The population is predominantly tribal, with the Mizo ethnic group making up around 94% of the total population. The Mizo people are part of the broader Sino-Tibetan ethnic group and speak Mizo, a Tibeto-Burman language, as their primary language, although English and Hindi are also used in formal contexts. Mizoram's population is relatively young, indicating a strong labor force potential. Mizoram's population growth rate between 2001 and 2011 was 23.48%, higher than the national average, though it is expected to stabilize in the future, reflecting broader demographic transitions. The fertility rate in the state is slightly above replacement levels, standing at 2.4 children per woman, which indicates ongoing demographic change (Statistical handbook of Mizoram 2022).

CHAPTER 4

MATERIALS AND METHODS

The reproductive biology of *Parkia timoriana* (DC.) Merr. was carried out from 2021 to 2024 in the regions of Tanhril, Sairang, and Reiek, located in the state of Mizoram, India (Figure 3.1).

4.1. Monitoring of reproductive phenology

Phenological observations and measurements were conducted on ten healthy, mature trees located across various sites within the Indo-Burma biodiversity hotspot. *P. timoriana* commonly-known as tree beans or stink beans is an agroforestry tree species of tropical region. Reproductive phenological stages of *P. timoriana* were systematically monitored from 2021 to 2024. To comprehensively capture the full progression of each phenophase from initiation to senescence weekly observations were conducted at all the study sites. A semi-quantitative scale, adapted from the BBCH system, was employed to specifically characterize the reproductive development stages. This scale was constructed using quantitative data derived from the field observations. For each reproductive phenological stage, detailed descriptions were provided, supplemented by photographic documentation and graphical summaries that illustrated the presence or absence of each stage throughout the monitoring period. Upon concluding the phenological monitoring of the selected individuals, the most representative photographs were chosen to visually depict the key developmental stages of *P. timoriana*. These images were instrumental in aiding the codification of its reproductive phenology, as outlined by Sakar *et al.* (2019).

In addition to direct observations, selected trees were assessed using binoculars to qualitatively evaluate the relative abundance (hereafter referred to as abundance) of phenological events such as flowering, finished flowering, fruit formation, and matured fruit. This abundance was quantified using a modified scoring system based on the approach of Jensen (2008). For each phenological event, the abundance was

scored on a scale from 0 to 4, with 0 - indicating absence, 1 - representing low abundance (<25%), 2 - indicating moderate abundance (25–50%), 3 - corresponding to high abundance (50–75%), and 4 - signifying very high abundance (>75%). For each phenological event, the mean score from ten trees of *P. timoriana* was calculated to represent the abundance of that stage at the given site and time. In addition, the following reproductive phenological parameters were documented: (i) onset, defined as the date of the first flower in anthesis (Kumar *et al.*, 2023); (ii) duration, representing the interval between the first and last flower (Kumar *et al.*, 2023); (iii) peak flowering, as per Bishop and Schemske (1998); (iv) mean flowering amplitude, which denotes the quantity of flowers produced per unit of time (Newstrom *et al.*, 1994); (v) flowering synchrony, which represents the extent of overlap in flowering events among individuals (Augspurger, 1983); and (vi) fruit formation, encompassing both development and retention (Kumar *et al.*, 2023). The six variables of flowering phenology, excluding synchrony, were assessed for both individual plants and the entire population.

4.1.1. Onset (Floral initiation)

To estimate floral initiation (onset), ten representative individuals at the site were monitored, and the mean values of the first flowers observed were recorded from the sample trees. These mean values served as indicators of floral initiation for each individual plant. For the entire population, the first flower recorded across all individuals was used to define the overall floral initiation.

4.1.2. Duration of flowering

The flowering duration was determined as the time interval between the mean values of the first and last flowers for each selected individual plant. For the entire population, it was determined as the duration between the first and last flowers observed across all individuals.

4.1.3. Peak flowering

Peak flowering was calculated as the mean flowering date, determined by averaging the census dates during which an individual was in bloom.

4.1.4. Mean flowering amplitude

Flowering amplitude was estimated by monitoring a total of ten days during the flowering period. The number of flowers was counted on each census date for ten selected individuals (Newstrom *et al.*, 1994).

4.1.5. Fruit formation

To determine the date of fruit formation, we monitored any changes in flower structure that indicated successful pollination. Subsequently, we observed the development of the fruit, marking the date when the first visible signs of fruit appeared, such as swelling of the ovaries. This date was considered as the fruit formation date.

4.1.6. Flowering synchrony

Flowering synchrony within an individual plant was defined as the extent to which its blooming period coincided with the blooming periods of other plants within the population. Synchrony was quantified using the method outlined by Augspurger (1983), as modified by Primack (1980). For each individual, the overlap in flowering duration with other individuals was estimated. The synchrony index (x) for an individual plant (i) was calculated as follows: the synchrony of a given individual with its conspecifics, denoted as x , is defined as:

$$x_i = \frac{1}{n-1} \times \frac{1}{f_i} \sum_{j=1}^n e_j \neq 1$$

where,

x_i = flowering synchrony index

e_j = number of days that individual 'i' and 'j' was flowering synchronously, with $j \neq i$

f_i = number of days individual 'i' was in flowering

n = number of flowering individuals in population

4.2 Impact of climatic variables on phenophase events

Plants are the most suitable organisms to study the effects of climatic variables in phenoevents because they are sedentary and thus encounter all climatic conditions experienced in their natural habitat (Gordo & Sanz, 2010). Climatic variables especially, temperature and rainfall significantly influence the phenological events of

plants (Gordo & Sanz, 2010; Barrett & Brown, 2021). The meteorological data employed in the present study were retrieved from the POWER Project, managed by the NASA Langley Research Center (LaRC). A total of ten mature individuals were marked and phenological events were observed at regular intervals and marked with acrylic paint. The incidence of reproductive phenophases such as flowering, finished flowering, fruit formation, and matured fruit in relation to temperature, precipitation, relative humidity, wind speed and photosynthetically active radiation was qualitatively evaluated by visual observation and also with the help of binoculars on marked individuals.

4.3. Floral biology

4.3.1. Anthesis time and anther dehiscence pattern

The anthesis phase, characterized by the full opening and functional maturation of a flower, and anther dehiscence, the process of pollen release from the anther, were observed in randomly selected floral samples ($n = 50$) of *P. timoriana* across the entire flowering period. The timing and pattern of anther dehiscence were documented in both field and laboratory settings, utilizing a 20x magnification lens. Observations were conducted at two-hour intervals, and environmental variables such as temperature, humidity, and wind speed were recorded concurrently. Flower samples were bagged with fine nylon mesh (200 mesh i.e., 74 μm) to prevent mechanical damage and cross-contamination of pollen. Anther dehiscence was defined as the point at which a rupture in the anther lobe was visually confirmed (Wani *et al.*, 2022; Khanduri *et al.*, 2019; Li *et al.*, 2018; Khanduri *et al.*, 2013). This study investigated the temporal and environmental factors that induce anther dehiscence.

4.3.2. Stigma receptivity analysis

Stigma receptivity was evaluated using a peroxidase-based hydrogen peroxide test, as described by Dafni (1992). This test relies on the enzymatic reaction between peroxidase present on the stigma and hydrogen peroxide, producing oxygen bubbles as an indication of receptivity. For this test, flower stigmas were carefully removed using fine forceps to avoid any damage, and immediately immersed in a 3% hydrogen peroxide solution for 3 minutes (Osborn *et al.*, 1988). A positive reaction was

identified by the appearance of gas bubbles on the stigma surface, and receptivity was quantified on a scale from 0 to 9, reflecting the intensity of the bubbling (Rashid *et al.*, 2023; Wani *et al.*, 2022; Khanduri *et al.*, 2019; Li *et al.*, 2018; Khanduri *et al.*, 2013). Observations were conducted at different time blocks, each starting at 2-hour intervals (i.e., 05:00–07:00, 07:00–09:00, 09:00–11:00, and so on), with ten replicates per time block, to evaluate temporal variations in stigma receptivity.

In addition to the peroxidase test, stigma receptivity was further analyzed through esterase activity using α -Naphthyl acetate as a substrate, following the method of Pearse (1972) and Dafni (1992). All floral structures except the pistils were excised, and the isolated pistils were immersed in Solution A (5 mg α -Naphthyl acetate dissolved in acetone, phosphate buffer pH 6.8, 10% sucrose, and 25 mg fast blue salt) for 30 minutes in a humidity chamber at 25 °C. A control (Solution B) was prepared in the same manner but without the substrate (α -Naphthyl acetate). Following incubation, the pistils were rinsed with phosphate buffer (pH 6.8), and esterase activity was observed on the stigma surface. Stigma receptivity was ranked based on esterase activity as follows: (–) no reaction, (+) weak positive reaction, (++) strong positive reaction, and (+++) very strong positive reaction (Souza *et al.*, 2016; Dafni & Maués 1998).

4.4. Pollen morphology examination

Pollen grains collected during the study were subjected to acetolysis following the method outlined by Younis *et al.* (2021). Flower samples containing pollen grains were initially preserved in 5 ml of glacial acetic acid and then manually crushed with a glass rod to release the pollen grains. The samples were centrifuged at 4,000 rpm for 20 min. to separate the pollen from the supernatant. The resulting residue was treated with an acetolysis mixture composed of 1 part concentration H_2SO_4 and 9 parts $(\text{CH}_3\text{CO})_2\text{O}$, and then heated in a water bath at boiling temperature for 3–4 min. After cooling, the mixture was centrifuged again, and the pollen was thoroughly rinsed with distilled water to remove any residual reagents. The prepared pollen was then suitable for examination via light microscopy (LM) and scanning electron microscopy (SEM).

For light microscopy, acetolysed pollen grains were mounted on glass slides using glycerine jelly prepared following the method outlined by Alyas *et al.* (2021). Fifty milliliters of distilled water were heated on a hot plate, and 35 gm of gelatin were gradually added while keeping the temperature between 70°C-80°C. Once a viscous solution was formed, 35 gm of glycerol and a small amount of phenol crystals were incorporated into the mixture. To impart a pink color, 0.1% safranin was added. The solution was then allowed to solidify at room temperature. Prepared pollen slides were observed under light microscopy at magnifications of 10X, 20X, and 40X, and the palynological characteristics were examined. For SEM, pollen grains were attached to stubs using adhesive tape and then gold-coated to a thickness of 35 nm using a sputter coater. The samples were subsequently examined with a JEOL JSM-6360 SEM to capture high-resolution images of the pollen grains and their surface ornamentation.

4.5. Pollinators and their foraging behaviour

Pollinators of *P. timoriana* were observed for over 24 hours during the flowering period for three consecutive years (2021 to 2023). To determine the identity of floral visitors and their behaviour, direct observations were made. The observations were taken from a distance such that floral visitors could be easily monitored, without disturbing their foraging behaviour. Binoculars, stopwatch, and Nikon D5600 SLR camera were used to record the observations. A total of 15–30 inflorescences per tree were monitored, and the number of pollinator visitors was recorded across 10 trees. During the peak flowering period, pollinator visits were documented at two-hour intervals over a 24-hour cycle. Both diurnal and nocturnal visitors were observed continuously at various times of the day. Only foragers that directly interacted with the flowers, making contact with the reproductive parts, were included in the observations (Anjum *et al.*, 2025; Khan *et al.*, 2023b; Yaqoob & Nawchoo, 2016; Talavera *et al.*, 2001).

4.6. Mating systems

The breeding systems in *P. timoriana* were evaluated through a series of manual experiments after identifying the peak receptive stage of the stigma *viz.* autogamy (self-pollination), geitonogamy (pollination between flowers of the same tree) and

xenogamy (pollination between flowers of different trees) were carried out along with open pollination (control). In each of the cases, flowers/inflorescences were bagged one day prior to anthesis and pollinations were performed at a suitable standardized stage of flower which depicted the highest receptivity. Twenty flowers were bagged, pollinated and observed till fruit set for breeding experiments. Pollination experiments were done during the peak period of flowering for three consecutive years (2021-2024).

4.6.1. Natural/ Open pollination (Control)

Natural/open pollination is the type of breeding occurring naturally without any simulated condition. Twenty flowers were randomly selected, tagged, and monitored until fruit development. Matured fruits were then collected, and the fruit set percentage was calculated.

4.6.2. Autogamy (Self-pollination)

To test autogamy, 20 flowers were selected, and pollination bags were placed over them one day prior to anthesis to prevent cross-pollination. The receptive stigma was then pollinated with pollen grains from the same flower. Following pollination, the flowers were re-bagged and periodically monitored until either abscission or fruit development occurred. The fruit set percentage was also determined.

4.6.3. Geitonogamous pollination

To assess the percentage of geitonogamy, flower buds were emasculated before anthesis, and their stigmas were pollinated with pollen grains from different flowers on the same plant. The flowers were then covered with mesh cloth bags. This experiment was performed on 20 flowers, and the fruit set percentage was monitored.

4.6.4. Xenogamous pollination

For the xenogamous pollination experiment, 20 flowers were selected and emasculated prior to anthesis. The stigmas of these flowers were then dusted with pollen grains collected from flowers of different plants belonging to other populations and re-bagged. The flowers were subsequently observed until mature fruits developed, and the percentage of fruit set was recorded.

4.7. Relative contribution of nocturnal and diurnal pollinators to the reproductive success of *P. timoriana*.

4.7.1. Experimental design and pollinator treatments

Inflorescences of *P. timoriana* were enclosed in bags prior to anthesis to assess the impact of diurnal and nocturnal pollination on pod and seed production. This experimental design aimed to restrict pollinator access. To achieve this, nylon mesh bags (50 cm × 30 cm, 200 mesh, 74 µm) were employed to limit pollinator visitation while controlling exposure to pollinators. The bags were securely fastened around the inflorescences, ensuring full coverage of the flowers and tight fixation at the base of the branches using integrated strings, thereby preventing pollinator access. Selection of trees was based on multiple criteria to ensure uniform experimental conditions, including availability of flowers for consistent treatment distribution. Inflorescences at similar stages of floral development were chosen from all trees. Pollination treatments were applied to evaluate the effects of diurnal and nocturnal pollinators (Figures 4.1. and 4.2.). A total of 80 inflorescences from 15 trees (4 to 6 inflorescences per tree) were subjected to the treatments (Singh *et al.*, 2024) (Figures 4.1. and 4.2.).

4.7.1.1. Diurnal pollination: Inflorescences were enclosed in bags overnight, with the bags removed once diurnal pollinators began foraging on the inflorescences (bagging period from 16:40 to 05:00 h).

4.7.1.2. Nocturnal pollination: Inflorescences were exposed to nocturnal pollinators and then bagged before diurnal pollinators became active (bagging period from 05:00 to 16:40 h).

4.7.1.3. Open pollination: Inflorescences were labeled and left unbagged, permitting access to both nocturnal and diurnal pollinators.

4.7.1.4. Pollinator exclusion: Some inflorescences were bagged both during the day and night to determine whether fruit set occurred in *P. timoriana* in the absence of pollinators.

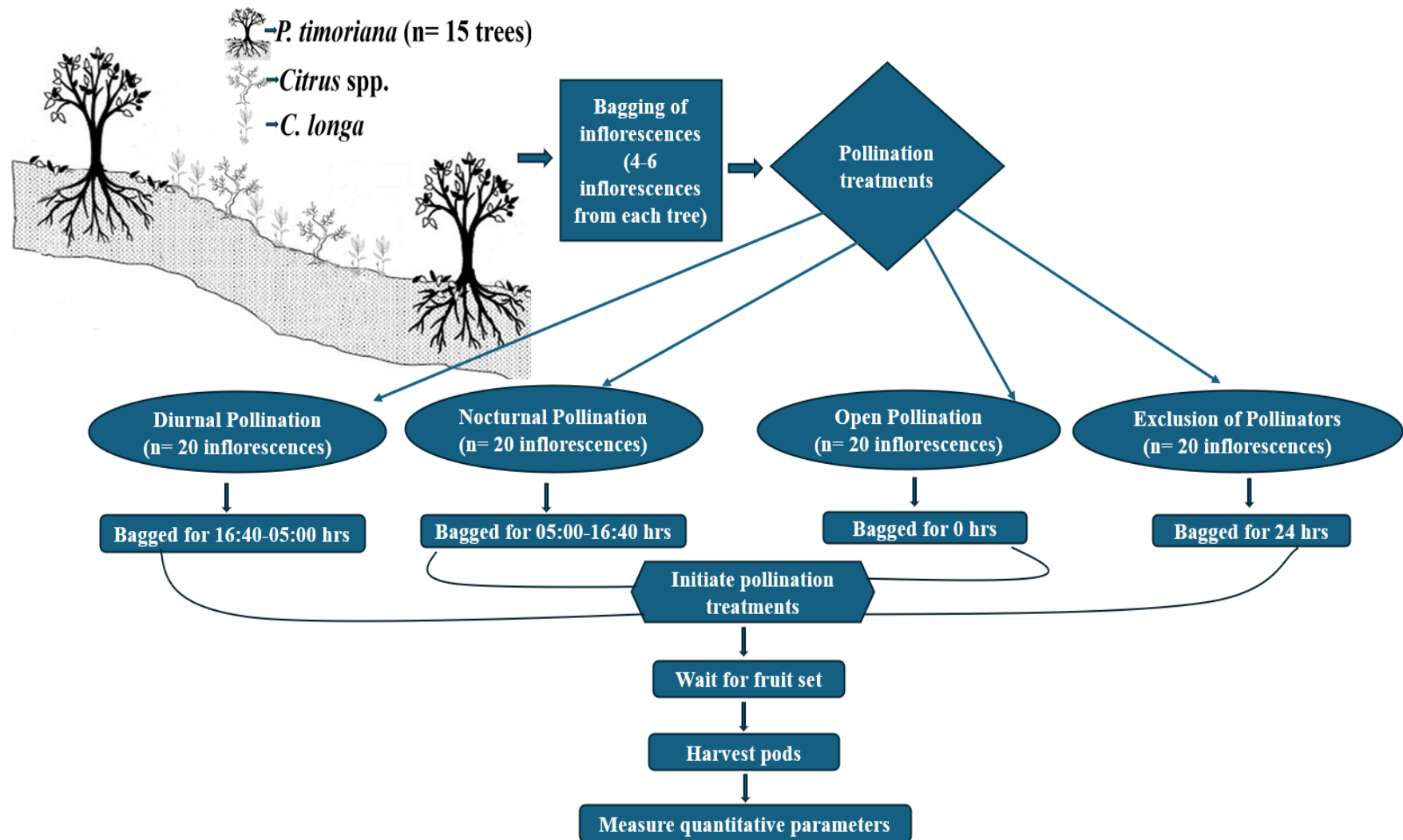


Figure 4.1. Conceptual plot of the experimental design.

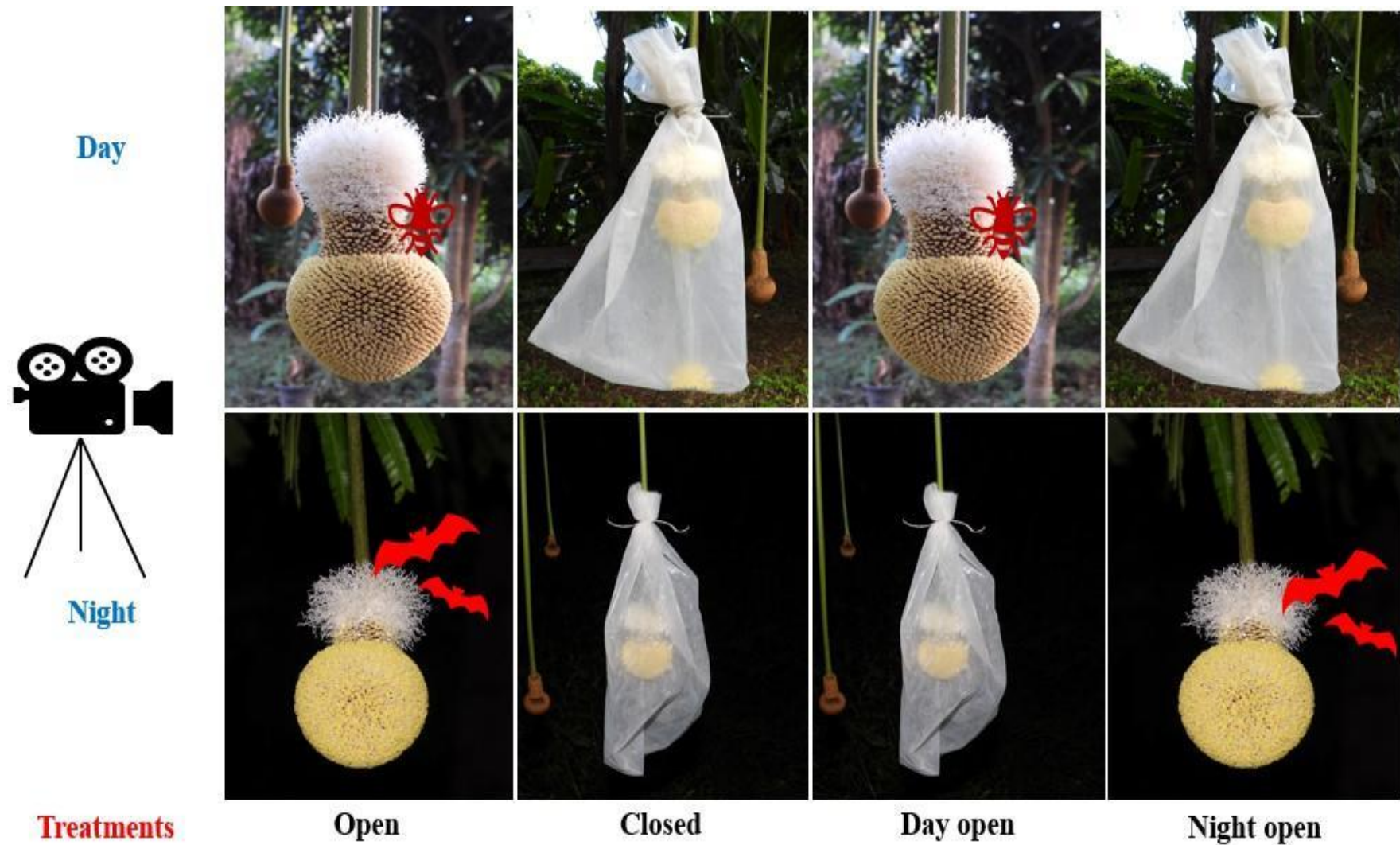


Figure 4.2. The four-pollination treatments (Open, Closed, Day open, and Night open) of the experimental design.

The pollinator exclusion treatment involved permanently covering inflorescences with nylon mesh bags (Figure 4.2.). These bags were removed when the styles, representing the receptive female tissue, began to wilt, indicating the onset of fruit set. Fruit set is defined as the stage in fruit development when fertilized ovules begin to mature, serving as a critical indicator of pollination success.

4.7.2. Harvesting and yield measurements

Fruits were collected in April, coinciding with the optimal harvesting period when all pods had reached full maturity. The identities of the trees from which the pods were sourced were carefully documented. In the laboratory, seeds were extracted from the pods, and their individual weights (in mg) were recorded using a precision scale with milligram accuracy. Seed length and diameter were measured with a digital caliper to the nearest 0.1 mm. Furthermore, the number of pods per capitulum and the number of seeds per pod were recorded for each experimental treatment (Singh *et al.*, 2024).

4.8. Pollen production, pollen- ovule ratio and pollen volume

4.8.1. Pollen production and pollen- ovule ratio

Flower and pollen production per tree were evaluated on ten randomly selected, marked trees of the species, with the same trees being monitored and sampled annually. To estimate pollen production, the total number of inflorescences per tree was first counted. The number of flowers per inflorescence was then determined by counting flowers on twenty randomly selected inflorescences from the crown of each tree. Additionally, twenty-five flowers were harvested from each tree, and the number of stamens was counted manually. The total number of flowers per tree was calculated by multiplying the number of flowers per inflorescence by the total number of inflorescences per tree (Kumar *et al.*, 2021; Khanduri *et al.*, 2019; Khanduri & Kumar, 2017a; Khanduri *et al.*, 2015a; Khanduri *et al.*, 2015b).

To estimate pollen grain production per flower and per tree, the number of pollen grains per anther was first counted from ten randomly selected flower buds on each tree. Additionally, five anthers from each flower were examined to determine the number of pollen grains per anther, following the method outlined by Molina *et al.* (1996). The average number of pollen grains per anther, derived from the fifty anthers,

was then used as the estimate for pollen grains per anther. Pollen grain production per tree was calculated by multiplying the average number of stamens per flower by the number of flowers per tree and then multiplying the result by the average number of pollen grains per anther (Kumar *et al.*, 2021; Khanduri *et al.*, 2019; Khanduri & Kumar, 2017a; Khanduri & Kumar, 2017b; Khanduri *et al.*, 2015a; Khanduri *et al.*, 2015b). The pollen-ovule ratio was calculated by dividing the estimated number of pollen grains per flower by the number of ovules per flower, as described by Cruden (1977).

$$P/O = \frac{\text{Pollen count per anther} \times \text{Number of anthers per flower}}{\text{Number of ovules per flower}}$$

4.8.2. Pollen volume

Pollen volume was estimated following the methods outlined by Ganie (2021) and Zhang *et al.* (2009). Pollen grains from thirty randomly selected dehiscent anthers were placed in a drop of glycerine. The diameters of the polar and equatorial axes were measured at magnifications of 10x, 20x, and 40x using a Leica DM 2000 LED microscope. The volume of each pollen grain was subsequently calculated using the following formula:

$$V = \frac{\pi P E^2}{6}$$

where,

P = polar axis diameter.

E = equatorial axis diameter

4.9. Air-borne pollen density

Air-borne pollen density was estimated using slide hanging method and GRIPS-99M Rotation Impaction Sampler.

4.9.1. Slide hanging method

In this approach, airborne pollen density was assessed by suspending glass slides (75 × 25 mm) coated with silicone grease at an optimal height to accurately capture pollen

dispersal in the atmosphere (Khanduri, 2012). Slides were exposed on five distinct trees during the peak flowering period. For a continuous 24-hour cycle, slides were collected and examined hourly at various time intervals. Pollen grains were quantified by counting the number present within a 1 cm² area under a light microscope.

4.9.2. GRIPS-99M Rotation Impactation Sampler

A Rotation impactation sampler was employed to collect airborne pollen particles. The sampling head was equipped with two removable clear polystyrene rods, each providing a sampling surface measuring 1.59 mm by 32 mm. When inactive, the rods retracted into the sampling head. During operation, the motor rotated the sampling head at approximately 2400 revolutions per minute (RPM), generating centrifugal force that extended the rods downward at a 90° angle, causing pollen particles to impact onto their leading surfaces. The quantity of pollen collected was directly proportional to the volume of air sampled. Prior to sampling, the rods were coated with silicone grease. Rods were replaced and analyzed hourly over a 24-hour period during peak flowering. Collected rods were mounted on a specialized grooved stage adapter for microscopic examination. Pollen grain concentration per unit air volume was subsequently calculated using the following formula:

$$\text{Concentration of pollen grains} = \frac{\text{Total pollen grains on the rods}}{\text{RPM} \times K \times M}$$

where, RPM= 2400

K= Retracting “Type I” rod constant = 0.0197

M= Sampling period (minutes)

4.10. Analysis of pollen viability

Pollen viability is defined as the ability of pollen grains to undergo post-pollination processes and lead to successful fertilization. Successful fertilization and fruit set depend on the viability of the pollen grains (Shivanna, 2003; Shivanna & Tandon, 2014). Treatment with nonvital stains allows for the coloration of the cell contents of pollen grains, providing a means to assess viability (Shivanna & Rangaswamy, 1992). Various pollen viability tests, including Alexander staining (Alexander, 1969), 2,3,5-Triphenyl tetrazolium chloride test (Shivanna & Rangaswamy, 1992), and

Fluorochromatic reaction (FCR) (Shivanna & Rangaswamy, 1992), test were employed to evaluate pollen grain viability.

4.11. Nectar analysis

Nectar present in the flower serves as the food reward for pollinators and visitors. Type of pollinator, its constancy and visitation frequency are greatly influenced by the positioning of the nectary, quality and amount of nectar produced, temporal patterns of nectar secretion, its sugar ratios, and calorific content of the nectar. Nectar presence was evaluated by examining the inflorescences, and the volume of nectar secreted was measured to assess its quantifiability. Keeping all the aforementioned factors in mind, different aspects of nectar biology were studied, which are as follows.

4.11.1. Nectar volume

To determine the amount of nectar available at different intervals of time, the inflorescences ($n = 30$) were bagged one day prior to anthesis in randomly selected 10 trees and after anthesis, all the bags were removed and nectar was collected with the help of syringe (2 ml) and the nectar collected was stored in Eppendorf tube and the amount of nectar available was measured using an Eppendorf micropipette (100 and 10 μ L) at each hour, from 1600 h to next day 0500 h. Nectar was extracted without removing the flowers from the plant, taking extreme care so as not to damage the flowers. In another experiment, the total amount of nectar available in the inflorescence was collected by putting a glass beaker inside a mesh bag around the inflorescence one day before the anthesis and the amount of nectar available was measured using an Eppendorf micropipette (100 and 10 μ l).

4.11.2. Concentration of nectar

The concentration of sugar present in the nectar was measured with the aid of micro-capillary pipettes (5 μ l) and hand-held refractometer with automatic temperature compensation (Erma Inc., ERB-32). The nectar secreted from the inflorescence was determined and expressed sugar concentration in brix for each time block. The concentration of sugar in the nectar produced by inflorescences ($n = 30$) was measured at their habitat.

4.11.3. Amount of nectar sugars

Total sugars present in nectar were calculated using the formula (Dafni *et al.*, 2005).

$$y = 0.00226 + (0.00937 \times x) + (0.0000585 \times x^2)$$

where,

y = mg of sugar per μl , and

x = sugar concentration (reading from hand-held refractometer)

4.11.4. Energetic value of nectar

The energetic value of nectar was determined using the following formula (Dafni *et al.*, 2005).

$$\text{Energetic value of nectar (cal)} = 4y$$

$$\text{Energetic value of nectar (joule)} = 16.8y$$

where,

y = mg of sugar per μl

4.11.5. Analysis of sugars in nectar sample using HPLC

The concentrations of different types of sugar in nectar samples were estimated using HPLC with a Shimadzu LC-2050 C system coupled to a SEDEX 85 LT Evaporative Light Scattering Detector (ELSD). An IICMS/LCC-248 column was used for sugar separation, with the mobile phase comprising water and acetonitrile in a 20:80 ratio. The analysis was conducted under isocratic elution conditions with a flow rate of 1.4 ml per min, and the column oven temperature was maintained at 30°C to ensure consistent separation. The chromatographic run time was set to 10 minutes, with the mobile phase serving as the diluent for sample preparation. Nitrogen gas, supplied at a pressure of 2.5 bar, was used to facilitate evaporation in the ELSD, which was operated at a detector temperature of 65°C for optimal sensitivity. A gain setting of 4 was applied to the ELSD for effective detection of the analytes. These optimized conditions allowed for the precise quantification of glucose, fructose, and sucrose in nectar, ensuring reproducibility and reliability of the results for accurate sugar estimation.

4.11.6. Analysis of amino acids in nectar sample using HPLC

The following procedure was employed to analyze the amino acids in the nectar sample using HPLC with a Shimadzu LC-2050 C system coupled with a Shimadzu RF-20A fluorescence detector. A Phenomenex Gemini NX C18 column (250 x 4.6 mm, 5 µm) was utilized for the chromatographic separation. The mobile phase consisted of two components: Phase A was a potassium phosphate buffer adjusted to the desired pH with O-phthalaldehyde (OPA), and Phase B was a mixture of methanol, acetonitrile, and water in a ratio of 40:45:15. A gradient elution mode was employed with the following gradient program: at 0.35 minutes, Phase B was set to 10%; at 45.00 minutes, Phase B was increased to 45%; at 50.00 minutes, Phase B was adjusted to 100%; at 57.00 minutes, Phase B was maintained at 100%; at 58.00 minutes, Phase B was decreased back to 10%; and the flow was stopped at 70.00 minutes. The flow rate was maintained at 1 ml per min, and a 1 µl sample was injected into the system. The column oven was set to 40 °C, while the autosampler was kept at 15 °C to preserve sample integrity. The fluorescence detection was carried out using the Shimadzu RF-20A detector. For sample preparation, water was used as the diluent. This method ensures the effective separation and detection of amino acids in the nectar sample, providing accurate and reliable results for subsequent analysis.

4.12. *In vitro* pollen germination

4.12.1. Effect of sucrose and plant growth regulators on pollen germination

The influence of growth hormones on pollen germination was investigated using four hormones: Indole-3-Acetic Acid, Indole-3-Butyric Acid, Gibberellic Acid, and Kinetin. Each hormone was tested at concentrations of 10, 20, 50, and 100 ppm. *In vitro* pollen germination experiments were performed using pollen obtained from freshly dehiscent anthers of various flowers. The pollen grains were filtered through a 100 µm sieve and incubated in an optimized culture medium. A factorial experimental design (Tuinstra & Wedel, 2000) was employed to evaluate the effects of sucrose and the four growth regulators on pollen germination, with distilled water serving as the control. Sucrose, recognized as a critical substrate for pollen germination in multiple species (Raina *et al.*, 2003), was tested at concentrations of 5, 10, 15, and 20%. Bulk

pollen was evenly distributed onto germination media within cavity slides and maintained under ambient laboratory conditions. Germination progress was recorded at 24, 48, and 72 hours following inoculation (Khanduri *et al.*, 2019; Kumar *et al.*, 2016). Pollen grains were deemed germinated, as outlined by Beltrán *et al.* (2019) and Tuinstra & Wedel (2000).

4.12.2. Effect of temperature treatments on pollen germination and pollen tube growth

Cavity slides containing pollen grains suspended in Brewbaker & Kwack (1963) medium were incubated in darkness at controlled temperatures of 15, 20, 25, and 30°C. Germination progress was assessed 24 hours post-inoculation. Pollen grains were deemed germinated, as outlined by Beltrán *et al.* (2019) and Tuinstra & Wedel (2000).

4.13. Statistical analysis

Data was organized and stored in Excel worksheets using a tabular format of rows and columns, facilitating systematic processing and analysis as required. Quantitative variables and percentages are presented as mean $\pm$ standard error (SE). The normality of the data distributions was evaluated using the Shapiro-Wilk test. Depending on data characteristics, comparisons of means, correlation analysis, and regression analysis were analyzed using appropriate parametric or non-parametric statistical tests implemented in IBM SPSS Statistics Version 27, Statgraphics version XVII software package, and Minitab Version 21.3.1. Graphical representations were generated using Origin Pro 2022 and Microsoft Excel 365.

CHAPTER 5

RESULT

5.1. Monitoring of reproductive phenology

5.1.1. Reproductive phenology of *P. timoriana* across three sites (Sairang, Tanhril, and Reiek), Mizoram, India from 2021 to 2024

The reproductive phenology of *P. timoriana* was analyzed across three geographically distinct sites of Mizoram, viz., Sairang, Tanhril, and Reiek over the period 2021 to 2024. Key variables, such as the onset of flowering, flowering duration, peak flowering dates, amplitude, flowering synchrony, and fruit formation dates, were studied to understand the spatio-temporal variations in the species' reproductive cycle. The following sections summarize the findings for all three sites.

5.1.1.1. Onset of flowering

The onset of flowering across the three sites showed variations over the years. At the Sairang site, the mean plant values for flowering onset were recorded on the 7th of November in 2021-2022, with a slight delay to the 6th of November in 2022-2023, and further delayed to the 12th of November in 2023-2024. For the population, the onset occurred on the 1st of November in both 2021-2022 and 2022-2023 but shifted to the 7th of November in 2023-2024 (Table 5.1.). At Tanhril, the onset for the mean plant values occurred on the 18th of September in 2021-2022, shifted to the 11th of September in 2022-2023, and delayed further to the 24th of September in 2023-2024. For the population at Tanhril, the onset occurred on the 14th of September in 2021-2022, moved to the 7th of September in 2022-2023, and shifted to the 18th of September in 2023-2024 (Table 5.2.). At Reiek, the onset of flowering for the mean plant values occurred on the 28th of September in 2021-2022, shifted to the 22nd of September in 2022-2023, and occurred on the 27th of September in 2023-2024. For the population, the onset occurred on the 23rd of September in 2021-2022, moved to the 19th of

September in 2022-2023, and shifted to the 28th of September in 2023-2024 (Table 5.3.). In all cases, there was a gradual delay in the onset of flowering over the years, particularly at Sairang and Tanhril.

5.1.1.2. Flowering duration

Flowering duration showed both site-specific and temporal trends. At Sairang, the flowering duration for the plant extended from 50 days in 2021-2022 to 53 days in 2022-2023 and 54 days in 2023-2024. The population's flowering duration ranged from 62 days in 2021-2022 to 65 days in 2022-2023 and 64 days in 2023-2024 (Table 5.1.). At Tanhril, the plant flowering duration was 74 days in 2021-2022, decreased to 72 days in 2022-2023, and further reduced to 69 days in 2023-2024. The population's flowering duration at Tanhril ranged from 88 days in 2021-2022 to 89 days in 2022-2023, dropping to 83 days in 2023-2024 (Table 5.2.). At Reiek, the plant flowering duration was 68 days in 2021-2022, increased to 71 days in 2022-2023, and decreased to 66 days in 2023-2024. The population's flowering duration ranged from 85 days in 2021-2022 to 81 days in 2022-2023, and 80 days in 2023-2024 (Table 5.3.). Overall, flowering duration generally increased at Sairang, while it decreased slightly at Tanhril and Reiek over the years.

5.1.1.3. Peak of flowering

The peak of flowering for plants and populations showed varying trends. At Sairang, the peak of flowering for the plants occurred on the 1st of December in 2021-2022, shifting to the 27th of November in 2022-2023, and further to the 3rd of December in 2023-2024. For the population, peak flowering was observed on the 28th of November in 2021-2022, shifting to the 23rd of November in 2022-2023, and to the 30th of November in 2023-2024 (Table 5.1.). At Tanhril, the peak of flowering for plants was on the 25th of October in 2021-2022, moved to the 17th of October in 2022-2023, and to the 29th of October in 2023-2024. For the population, peak flowering occurred on the 23rd of October in 2021-2022, shifted to the 14th of October in 2022-2023, and to the 25th of October in 2023-2024 (Table 5.2.). At Reiek, the peak of flowering for plants occurred on the 29th of October in 2021-2022, shifted to the 24th of October in

2022-2023, and to the 1st of November in 2023-2024. For the population, the peak flowering occurred on the 24th of October in 2021-2022, moved to the 19th of October in 2022-2023, and to the 29th of October in 2023-2024 (Table 5.3.). These shifts in peak flowering reflect variations in the timing of flowering across all three sites, with notable delays in some years.

5.1.1.4. Amplitude of flowering

Amplitude, which measures the intensity of flowering, generally increased over the years. At Sairang, amplitude for plants increased from 6.48 in 2021-2022 to 7.21 in 2022-2023, before slightly decreasing to 7.07 in 2023-2024. For the population, amplitude increased from 5.48 in 2021-2022 to 6.17 in 2022-2023, reaching 8.86 in 2023-2024 (Table 5.1.). At Tanhril, amplitude for plants rose from 9.03 in 2021-2022 to 10.10 in 2022-2023 and remained steady at 9.52 in 2023-2024. The amplitude for the population increased from 8.45 in 2021-2022 to 9.86 in 2022-2023, stabilizing at 9.59 in 2023-2024 (Table 5.2.). At Reiek, amplitude for plants increased from 8.38 in 2021-2022 to 9.76 in 2022-2023 and decreased slightly to 8.97 in 2023-2024. For the population, amplitude increased from 8.03 in 2021-2022 to 9.17 in 2022-2023, before slightly decreasing to 8.79 in 2023-2024 (Table 5.3.). Overall, amplitude increased across the sites, especially for the population.

5.1.1.5. Flowering synchrony

Flowering synchrony, which measures the coordination of flowering events across the population, exhibited slight variations. At Sairang, synchrony increased from 0.81 in 2021-2022 to 0.82 in 2022-2023 and slightly improved to 0.84 in 2023-2024 (Table 5.1.). At Tanhril, synchrony decreased from 0.84 in 2021-2022 to 0.81 in 2022-2023 but recovered slightly to 0.83 in 2023-2024 (Table 5.2.). At Reiek, synchrony increased from 0.80 in 2021-2022 to 0.83 in 2022-2023 and remained stable at 0.83 in 2023-2024 (Table 5.3.). These trends suggest varying degrees of flowering synchrony, with a slight improvement in synchrony at Sairang and Reiek, but a slight decrease at Tanhril.

5.1.1.6. Fruit formation

The timing of fruit formation showed delays in the final year at all three sites. At Sairang, fruit formation for plants occurred on the 12th of December in 2021-2022, shifted to the 7th of December in 2022-2023, and further delayed to the 14th of December in 2023-2024. For the population, fruit formation occurred on the 13th of December in 2021-2022, shifted to the 10th of December in 2022-2023, and moved to the 15th of December in 2023-2024 (Table 5.1.). At Tanhril, fruit formation for plants occurred on the 29th of October in 2021-2022, shifted to the 24th of October in 2022-2023, and further delayed to the 1st of November in 2023-2024. For the population, fruit formation occurred on the 31st of October in 2021-2022, shifted to the 26th of October in 2022-2023, and further delayed to the 4th of November in 2023-2024 (Table 5.2.). At Reiek, fruit formation for plants occurred on the 2nd of November in 2021-2022, shifted to the 30th of October in 2022-2023, and further delayed to the 6th of November in 2023-2024. For the population, fruit formation occurred on the 5th of November in 2021-2022, shifted to the 6th of November in 2022-2023, and moved to the 11th of November in 2023-2024 (Table 5.3.).

Table 5.1. Reproductive phenology of *P. timoriana* for the site Sairang.

Observed variables	2021-2022	2022-2023	2023-2024
Onset (mean plant values)	7 th November	6 th November	12 th November
Onset (population)	1 st November	1 st November	7 th November
Flowering duration (plant)	50 d	53 d	54 d
Flowering duration (population)	62 d	65 d	64 d
Peak of flowering (plant)	1 st December	27 th November	3 rd December
Peak of flowering (population)	28 th November	23 rd November	30 th November
Amplitude (plant)	6.48	7.21	7.07
Amplitude (population)	5.48	6.17	8.86
Flowering synchrony	0.81	0.82	0.84
Fruit formation (plant)	12 th December	7 th December	14 th December
Fruit formation (population)	13 th December	10 th December	15 th December

Table 5.2. Reproductive phenology of *P. timoriana* for the site Tanhril.

Observed variables	2021-2022	2022-2023	2023-2024
Onset (mean plant values)	18 th September	11 th September	24 th September
Onset (population)	14 th September	7 th September	18 th September
Flowering duration (plant)	74 d	72 d	69 d
Flowering duration (population)	88 d	89 d	83 d
Peak of flowering (plant)	25 th October	17 th October	29 th October
Peak of flowering (population)	23 rd October	14 th October	25 th October
Amplitude (plant)	9.03	10.10	9.52
Amplitude (population)	8.45	9.86	9.59
Flowering synchrony	0.84	0.81	0.83
Fruit formation (plant)	29 th October	24 th October	1 st November
Fruit formation (population)	31 st October	26 th October	4 th November

Table 5.3. Reproductive phenology of *P. timoriana* for the site Reiek.

Observed variables	2021-2022	2022-2023	2023-2024
Onset (mean plant values)	28 th September	22 nd September	27 th September
Onset (population)	23 rd September	19 th September	28 th September
Flowering duration (plant)	68 d	71 d	66 d
Flowering duration (population)	85 d	81 d	80 d
Peak of flowering (plant)	29 th October	24 th October	1 st November
Peak of flowering (population)	24 th October	19 th October	29 th October
Amplitude (plant)	8.38	9.76	8.97
Amplitude (population)	8.03	9.17	8.79
Flowering synchrony	0.80	0.83	0.83
Fruit formation (plant)	2 nd November	30 th October	6 th November
Fruit formation (population)	5 th November	6 th November	11 th November

5.1.2. Codification of BBCH scale in reproductive biological events of *P. timoriana*

Bleiholder *et al.* (1991) and Hack *et al.* (1992) introduced the BBCH scale, which provides a standardized coding system for identifying the phenological stages for most of the monocotyledonous and dicotyledonous plant species. This system uses a decimal code that categorizes both primary and secondary growth phases, inclusive of reproductive phases. The BBCH measure for monocots and dicots defines ten prime growing phases, 0 to 9 tagged numbers (Hack *et al.*, 1992). In addition to these primary phases, developmental stages are indicated by a two digit number representing incremental developing phases within the major stages. The scale under this study applied to *P. timoriana*, considered only the critical phases responding to multiplicative biological events, beginning with inflorescence progression (stage 5) and concluding with fruit maturation or senescence (stage 8). The assignment of lag Phase does not strictly follow the 0-9 numbering but instead aligns with the most appropriate official descriptors measuring BBCH parameters (Hack *et al.*, 1992). Figures 5.1. and 5.2. illustrate exclusive reproductive biological events recorded in *P. timoriana* tree samples from the study sites. In the following write up, we detail each sexual propagation steps and stage corresponding to specific area and time period:

Primary proliferation Phase 5: Ball or Globe (inflorescence) appearance

50: Reproductive bud bulging began

51: Bud swelling and reached full size.

53: Globe burst: the endings of the sepals enclosing the flowers are evident. This phase is comparable nearly to phase 51, but the flower ball displays a greater extent of maturity. It exhibit approximately at the comparable pattern as phase 51.

Primary proliferation Phase 6: Flowering

60: First flower opened

61: Flowering Initiation: approximately 10% of the inflorescence have anthesis, with florets opening sequentially starting from top to the base of the globe.

62: Approx. 20% globe opening

63: Approx. 30% globe opening



Figure 5.1. Reproductive phenological growth stages of *P. timoriana* as per BBCH scale.



Figure 5.2. Reproductive phenological growth stages of *P. timoriana* as per BBCH scale.

64: Approx. 40% globe opening: The top part of the inflorescence was white in colour and yellow colour at the base of the terminal.

66: Full flowering: over 70% of flowers are open, with numerous styles and stigmas visible.

67: Full flowering: over 80% of flowers are open, with numerous styles and stigmas visible. Nectar droplets can be observed at the neck of the inflorescence.

68: Full globe opening: at least 90% of inflorescence open, many visible pistils observed.

69: End of flowering: some inflorescence have fallen or dried, and the fruits are just beginning to appear.

Primary proliferation Phase 7: Development of fruit

70: Visibility of immature fruits

72: 20% of optimal fruit size

75: 50% of optimal fruit size

76: 60% of optimal fruit size

78: 80% of optimal fruit size

79: 90% of optimal fruit size

Primary proliferation Phase 8: Senescence phase

81: Onset of maturation and color transition: the fruit's skin begins to turn black.

85: Advanced coloring: fruits have ripened to a black hue.

87: Beginning of drying of the fruits.

88: The onset of fruit consistency decline, which mirrors stage 87 but with a greater degree of maturity in the fruit. This stage occurred approximately simultaneously with stage 87.

5.1.3. Correlation of reproductive phenological events with environmental parameters

Spearman's rank correlation study was conducted to examine the relation between various reproductive phenological events (flowering, finished flowering, fruit formation, and matured fruit) and several environmental parameters. Significant correlations were observed between several environmental factors and the reproductive stages, underscoring the intricate interplay between environmental

conditions and plant reproductive phenology. Temperature (TM) exhibited a notable negative correlation with the onset of flowering ($r_s = -0.152, p = 0.042$), finished flowering ($r_s = -0.489, p < 0.001$) and fruit formation ($r_s = -0.675, p < 0.001$) (Table 5.4.). Maximum temperature (TMMA) showed a significant negative correlation with flowering ($r_s = -0.303, p < 0.001$) and finished flowering ($r_s = -0.586, p < 0.001$), as well as with fruit formation ($r_s = -0.697, p < 0.001$) (Table 5.4.). These findings advocates that higher temperatures may delay the initiation of flowering, the fruit formation, and the completion of the flowering process. In contrast, a significant positive correlation with matured fruit were observed for TM ($r_s = 0.305, p < 0.001$) and TMMA ($r_s = 0.578, p < 0.001$), indicating that warmer temperatures may enhance fruit maturation under certain conditions. Minimum temperature (TMMI) did not show significant effects on flowering ($r_s = -0.01, p = 0.894$) and matured fruit ($r_s = 0.023, p = 0.761$) but it was negatively associated with finished flowering ($r_s = -0.381, p < 0.001$) and fruit formation ($r_s = -0.624, p < 0.001$) (Table 5.4.). These findings suggest that cooler minimum temperatures may delay the transition from flowering to fruit development.

Specific humidity was positively associated with flowering ($r_s = 0.194, p = 0.009$), hinting that rising humidity may positively initiate flowering. However, it exhibited significant negative association with fruit formation ($r_s = -0.390, p < 0.001$) and matured fruit ($r_s = -0.328, p < 0.001$), suggesting that excess humidity may impair the later stages of fruit development (Table 5.4.). Relative humidity (RH) exhibited significant positive associations with flowering ($r_s = 0.399, p < 0.001$) and finished flowering ($r_s = 0.235, p = 0.001$), suggesting that higher humidity levels may favor these early reproductive stages. However, a strong significant negative correlation was found with matured fruit ($r_s = -0.766, p < 0.001$), implying that high relative humidity could hinder the maturation of fruit (Table 5.4.). Precipitation (PR) was efficiently and negatively associated with finished flowering ($r_s = -0.259, p < 0.001$) and fruit formation ($r_s = -0.399, p < 0.001$) (Table 5.4.). These results suggest that increased rainfall can inhibit the progression of flowering and fruit development. No significant correlation were observed with matured fruit ($r_s = -0.026, p = 0.729$) and flowering ($r_s = -0.083, p = 0.269$) (Table 5.4.).

Table 5.4. Spearman's rank correlation analysis between different reproductive phenological events and environmental parameters studied.

	Flowering		Finished flowering		Fruit formation		Matured fruit	
	r_s	p	r_s	p	r_s	p	r_s	p
TM	-0.152*	0.042	-0.489**	0.000	-0.675**	0.000	0.305**	0.000
TMMA	-0.303**	0.000	-0.586**	0.000	-0.697**	0.000	0.578**	0.000
TMMI	-0.010	0.894	-0.381**	0.000	-0.624**	0.000	0.023	0.761
QV	0.194**	0.009	-0.119	0.110	-0.390**	0.000	-0.328**	0.000
RH	0.399**	0.000	0.235**	0.001	0.007	0.921	-0.766**	0.000
PR	-0.083	0.269	-0.259**	0.000	-0.399**	0.000	-0.026	0.729
PS	0.029	0.701	0.026	0.733	0.13	0.081	-0.120	0.110
WS	0.036	0.636	0.242**	0.001	0.429**	0.000	-0.041	0.584
WSMA	-0.024	0.746	0.174*	0.019	0.370**	0.000	0.058	0.437
WSMI	-0.246**	0.001	-0.268**	0.000	-0.286**	0.000	0.525**	0.000
SSW	0.410**	0.000	0.212**	0.004	-0.002	0.982	-0.802**	0.000
RZSW	0.403**	0.000	0.209**	0.005	0.003	0.970	-0.816**	0.000
PAR	-0.213**	0.004	-0.465**	0.000	-0.584**	0.000	0.351**	0.000
Flowering	1	-	0.437**	0.000	0.107	0.151	-0.484**	0.000
Finished flowering	0.437**	0.000	1	-	0.663**	0.000	-0.515**	0.000
Fruit formation	0.107	0.151	0.663**	0.000	1	-	-0.348**	0.000
Matured fruit	-0.484**	0.000	-0.515**	0.000	-0.348**	0.000	1	-

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

Wind speed (WS) and maximum wind speed (WSMA) showed significant positive correlations with finished flowering ($r_s = 0.242^{**}$, $p < 0.01$) and fruit formation ($r_s = 0.429^{**}$, $p < 0.01$), and finished flowering ($r_s = 0.174^*$, $p < 0.05$) and fruit formation ($r_s = 0.370^{**}$, $p < 0.01$), respectively (Table 5.4.). However, neither WS or WSMA showed significant correlation with flowering ($r_s = 0.036$, $p > 0.05$) and matured fruit ($r_s = -0.041$, $p > 0.05$), and flowering ($r_s = -0.024$, $p > 0.05$) and matured fruit ($r_s = 0.058$, $p > 0.05$), respectively (Table 5.4.). Minimum wind speed (WSMI) exhibited a negative significant correlation with flowering ($r_s = -0.246^{**}$, $p < 0.01$), finished flowering ($r_s = -0.268^{**}$, $p < 0.01$), and fruit formation ($r_s = -0.286^{**}$, $p < 0.01$), but a significant positive correlation with matured fruit ($r_s = 0.525^{**}$, $p < 0.01$) (Table 5.4.). Surface soil wetness (SSW) and root zone soil wetness (RZSW) demonstrated significant positive correlations with flowering ($r_s = 0.410^{**}$, $p < 0.01$) and finished flowering ($r_s = 0.212^{**}$, $p < 0.01$), and flowering ($r_s = 0.403^{**}$, $p < 0.01$) and finished flowering ($r_s = 0.209^{**}$, $p < 0.01$), respectively (Table 5.4.). In contrast, SSW and RZSW were negatively correlated with matured fruit ($r_s = -0.802^{**}$, $p < 0.01$) and matured fruit ($r_s = -0.816^{**}$, $p < 0.01$), respectively (Table 5.4.). Photosynthetically active radiation (PAR) showed a significant negative correlation with flowering ($r_s = -0.213^{**}$, $p < 0.01$), finished flowering ($r_s = -0.465^{**}$, $p < 0.01$), and fruit formation ($r_s = -0.584^{**}$, $p < 0.01$), but positively correlated with matured fruit ($r_s = 0.351^{**}$, $p < 0.01$) (Table 5.4.).

Correlations among the reproductive phenological events revealed a clear progression. Finished flowering was positively correlated with both flowering ($r_s = 0.437^{**}$, $p < 0.01$) and fruit formation ($r_s = 0.663^{**}$, $p < 0.01$) but negatively correlated with matured fruit ($r_s = -0.515^{**}$, $p < 0.01$) (Table 5.4.). Flowering and fruit formation were positively correlated with finished flowering ($r_s = 0.663^{**}$, $p < 0.01$) and finished flowering ($r_s = 0.437^{**}$, $p < 0.01$); but negatively correlated with matured fruit ($r_s = -0.484^{**}$, $p < 0.01$) and matured fruit ($r_s = -0.348^{**}$, $p < 0.01$); respectively (Table 5.3). Finally, matured fruit was negatively correlated with flowering ($r_s = -0.484^{**}$, $p < 0.01$), finished flowering ($r_s = -0.515^{**}$, $p < 0.01$), and fruit formation ($r_s = -0.348^{**}$, $p < 0.01$) (Table 5.4.).

5.1.4. Simple regression analysis

Regression models were applied to identify the most significant relationships between various environmental variables and reproductive phenological events, as detailed in Table 5.5. Only models exhibiting a R^2 value greater than 40% and a highly significant correlation coefficient ($p < 0.001$) were considered, and their corresponding equations are presented here. The models demonstrating the strongest associations are highlighted. According to these models, the maturation of fruit could be reliably predicted using RZSW, with R^2 values ranging from 69.56 % to 40.17 %, SSW with R^2 values from 68.66% to 40.28%, and RH with R^2 values spanning from 62.94% to 43.23% (Table 5.5.). Additionally, fruit formation was modeled with TM yielding R^2 values from 51.34% to 42.23%, TMMA with R^2 values ranging from 49.30% to 40.83%, and TMMI with R^2 values between 43.00% and 40.64%. Furthermore, fruit formation itself was identified as a valuable predictor for finished flowering, with R^2 values ranging between 49.10 % and 43.44 % (Table 5.5.).

5.1.5. Stepwise multiple regression analysis of different reproductive phenological events vs environmental parameters

In the analysis for the Tanhril study site, environmental variables such as TM, PR, PS, and RZSW were automatically selected. Together, these factors accounted for 40.59% of the variability in the flowering stage. In contrast, for the Sairang study site, parameters including TM, TMMI, QV, WS, WSMA, WSMI, SSW, and RZSW, explained 46.00% of the variability in flowering. The optimal model for predicting flowering, based on AIC values, was: Flowering = $-2.03 + 0.0507 \text{ RH} + 17.00 \text{ WS} - 6.13 \text{ WSMA} + 130.2 \text{ WSMI} - 0.2792 \text{ PAR}$ (Table 5.6.). For Tanhril, a combination of TM, TMMA, TMMI, QV, RH, PR, WS, SSW, and RZSW explained 61.58 % of the variation in finished flowering. For Sairang, TM, TMMI, QV, WS, WSMA, WSMI, SSW, and RZSW explained 40.32% of the variability in finished flowering. The best-fit model for determining finished flowering, derived from AIC values, was: Finished flowering = $12.65 - 0.952 \text{ TM} + 0.412 \text{ TMMI} + 0.464 \text{ QV} + 11.31 \text{ WS} - 4.87 \text{ WSMA} + 150.5 \text{ WSMI} - 21.22 \text{ SSW} + 14.24 \text{ RZSW}$ (Table 5.6.).

Table 5.5. Simple regression between the different reproductive phenological events and environmental parameters studied.

Dependent Variable	Independent Variable (X)	Equation	R ²	Adjusted R ²	p-value
Matured fruit	RZSW	$(-2.09041 + 1.64819/X)^2$	69.56 %	69.39%	<0.001
Matured fruit	SSW	$(-1.71074 + 1.42902/X)^2$	68.66 %	68.49%	<0.001
Matured fruit	SSW	$(-0.452996 - 2.37674*\ln X)^2$	68.41 %	68.23%	<0.001
Matured fruit	RZSW	$(-0.59589 - 2.60017*\ln X)^2$	66.28 %	66.09%	<0.001
Matured fruit	RH	$(2.36655 - 0.000292712*X^2)^2$	62.94 %	62.73%	<0.001
Matured fruit	TMMA	$\sqrt{(-10.6598 + 0.0180307*X^2)}$	60.76 %	60.54%	<0.001
Matured fruit	RH	$(6.56122 - 0.685932*\sqrt{X})^2$	60.30 %	60.08%	<0.001
Matured fruit	RZSW	$-3.45383 + 2.70829/X$	60.14 %	59.92%	<0.001
Matured fruit	SSW	$-2.82285 + 2.3438/X$	59.15 %	58.92%	<0.001
Matured fruit	SSW	$-0.755748 - 3.88885*\ln X$	58.64 %	58.41%	<0.001
Matured fruit	RH	$(12.6048 - 2.78291*\ln X)^2$	58.44 %	58.20%	<0.001
Matured fruit	SSW	$8.8504 - 9.7484*\sqrt{X}$	57.62 %	57.39 %	<0.001
Matured fruit	RZSW	$-0.991335 - 4.25824*\ln X$	56.92 %	56.68 %	<0.001
Matured fruit	SSW	$4.9671 - 6.00925*X$	56.21 %	55.97 %	<0.001
Matured fruit	TMMA	$\sqrt{(-23.0224 + 0.954548*X)}$	55.62 %	55.37 %	<0.001
Matured fruit	RZSW	$9.35528 - 10.4768*\sqrt{X}$	54.94 %	54.69 %	<0.001
Matured fruit	TMMA	$-2.62923 + 0.00481795*X^2$	53.67 %	53.41 %	<0.001
Matured fruit	RH	$(-1.77325 + 173.2/X)^2$	53.10 %	52.83 %	<0.001
Matured fruit	TMMA	$\sqrt{(-47.6531 + 9.72477*\sqrt{X})}$	52.93 %	52.66 %	<0.001
Matured fruit	RZSW	$5.11069 - 6.36695*X$	52.78 %	52.52 %	<0.001
Matured fruit	SSW	$3.03576 - 4.37099*X^2$	52.59 %	52.33 %	<0.001
Matured fruit	RH	$3.81437 - 0.000471688*X^2$	52.33 %	52.07 %	<0.001
Fruit formation	TM	$(-2.128 + 53.9241/X)^2$	51.34 %	51.06 %	<0.001
Matured fruit	RH	$6.06397 - 0.0667986*X$	50.96 %	50.68 %	<0.001
Fruit formation	TM	$-3.71233 + 92.5695/X$	50.48 %	50.20 %	<0.001
Fruit formation	TM	$(8.54987 - 2.64763*\ln X)^2$	50.25 %	49.97 %	<0.001

Matured fruit	TMMA	$\sqrt{(-78.0937 + 24.6051 \cdot \ln X)}$	50.19 %	49.91 %	<0.001
Matured fruit	RH	$10.5295 - 1.10022 \cdot \sqrt{X}$	49.68 %	49.39 %	<0.001
Matured fruit	TMMA	$-5.96044 + 0.256086 \cdot X$	49.53 %	49.24 %	<0.001
Fruit formation	TM	$(5.81128 - 1.1561 \cdot \sqrt{X})^2$	49.37 %	49.08 %	<0.001
Fruit formation	TMMA	$(-3.11529 + 94.9827/X)^2$	49.30 %	49.01 %	<0.001
Finished flowering	Fruit formation	$0.178908 + 1.23542 \cdot \sqrt{X}$	49.10 %	48.81 %	<0.001
Fruit formation	TM	$14.4965 - 4.50539 \cdot \ln X$	48.55 %	48.26 %	<0.001
Matured fruit	RZSW	$3.00983 - 4.54851 \cdot X^2$	48.20 %	47.91 %	<0.001
Matured fruit	RH	$20.1879 - 4.45552 \cdot \ln X$	47.96 %	47.67 %	<0.001
Finished flowering	Fruit formation	$\sqrt{(0.216017 + 4.24756 \cdot \sqrt{X})}$	47.85 %	47.56 %	<0.001
Matured fruit	TMMA	$-12.5927 + 2.61365 \cdot \sqrt{X}$	47.30 %	47.00 %	<0.001
Fruit formation	TM	$9.79759 - 1.95895 \cdot \sqrt{X}$	47.29 %	47.00 %	<0.001
Fruit formation	TMMA	$(11.9288 - 3.48657 \cdot \ln X)^2$	47.03 %	46.73 %	<0.001
Fruit formation	TM	$5.28938 - 0.210948 \cdot X$	45.88 %	45.58 %	<0.001
Fruit formation	TM	$(1.83397 - 0.00284559 \cdot X)^2$	45.69 %	45.38 %	<0.001
Fruit formation	TMMA	$(7.32539 - 1.32226 \cdot \sqrt{X})^2$	45.65 %	45.35 %	<0.001
Fruit formation	TMMI	$-1.9572 + 41.984/X$	45.41 %	45.10 %	<0.001
Fruit formation	TMMA	$-5.18699 + 157.185/X$	45.04 %	44.74 %	<0.001
Matured fruit	TMMA	$-20.8097 + 6.62374 \cdot \ln X$	45.01 %	44.70 %	<0.001
Matured fruit	TMMA	$\sqrt{(26.107 - 617.877/X)}$	44.71 %	44.40 %	<0.001
Fruit formation	TMMI	$8.58337 - 2.81141 \cdot \ln X$	43.92 %	43.61 %	<0.001
Finished flowering	Fruit formation	$(0.160613 + 0.666867 \cdot \sqrt{X})^2$	43.44 %	43.12 %	<0.001
Matured fruit	RH	$-2.81638 + 276.185/X$	43.23 %	42.91 %	<0.001
Fruit formation	TMMI	$(-1.05107 + 23.5991/X)^2$	43.00 %	42.68 %	<0.001
Fruit formation	TMMI	$(4.94742 - 1.6066 \cdot \ln X)^2$	42.99 %	42.67 %	<0.001
Fruit formation	TM	$3.03015 - 0.00476397 \cdot X^2$	42.73 %	42.40 %	<0.001
Matured fruit	RZSW	$\sqrt{(-10.2655 + 8.01923/X)}$	42.62 %	42.29 %	<0.001
Fruit formation	TMMA	$19.6102 - 5.73979 \cdot \ln X$	42.52 %	42.20 %	<0.001
Fruit formation	TMMI	$6.45502 - 1.40179 \cdot \sqrt{X}$	42.46 %	42.13 %	<0.001

Fruit formation	TM	$\sqrt{-11.9179 + 291.958/X}$	42.23 %	41.90 %	<0.001
Fruit formation	TMMI	$(3.75716 - 0.807405*\sqrt{X})^2$	42.21 %	41.89 %	<0.001
Fruit formation	TMMI	$\sqrt{-6.79554 + 138.916/X}$	41.81 %	41.48 %	<0.001
Matured fruit	TMMA	$(-1.18907 + 0.0024017*X^2)^2$	41.65 %	41.32 %	<0.001
Matured fruit	SSW	$\sqrt{-8.30234 + 6.88183/X}$	41.21 %	40.88 %	<0.001
Fruit formation	TMMA	$12.0034 - 2.17132*\sqrt{X}$	41.08 %	40.75 %	<0.001
Matured fruit	SSW	$\sqrt{-2.23961 - 11.4331*\ln X}$	40.97 %	40.64 %	<0.001
Fruit formation	TMMA	$(2.07885 - 0.00216399*X^2)^2$	40.83 %	40.50 %	<0.001
Fruit formation	TMMI	$3.6357 - 0.170829*X$	40.64 %	40.31 %	<0.001
Matured fruit	TMMA	$7.25831 - 166.785/X$	40.30 %	39.97 %	<0.001
Matured fruit	SSW	$\sqrt{(26.009 - 28.6685*\sqrt{X})}$	40.28 %	39.94 %	<0.001
Matured fruit	RZSW	$\sqrt{-2.96225 - 12.5833*\ln X}$	40.17 %	39.84 %	<0.001

Table 5.6. Tabulated results of multiple linear regression of different reproductive phenological events vs environmental parameters studied.

Site	Dependent variable	Regression equation	Observed R^2	Adjusted R^2	Predicted R^2	AIC	BIC	Validation test R^2	p-value
Tanhril	Flowering	$-190.7 + 0.1589 \text{ TM} - 0.1154 \text{ PR} + 1.910 \text{ PS} + 7.109 \text{ RZSW}$	50.05 %	47.70 %	42.56 %	268.58	282.56	40.59 %	<0.001
Sairang	Flowering	$-2.03 + 0.0507 \text{ RH} + 17.00 \text{ WS} - 6.13 \text{ WSMA} + 130.2 \text{ WSMI} - 0.2792 \text{ PAR}$	51.97 %	49.12 %	46.37 %	241.19	257.32	46.00 %	<0.001
Tanhril	Finished flowering	$-23.44 - 1.964 \text{ TM} + 1.363 \text{ TMMA} + 1.333 \text{ TMMI} - 0.946 \text{ QV} + 0.1946 \text{ RH} - 0.0910 \text{ PR} + 4.28 \text{ WS} + 20.69 \text{ SSW} - 15.14 \text{ RZSW}$	71.43 %	68.21 %	64.55 %	227.90	252.01	61.58 %	<0.001
Sairang	Finished flowering	$12.65 - 0.952 \text{ TM} + 0.412 \text{ TMMI} + 0.464 \text{ QV} + 11.31 \text{ WS} - 4.87 \text{ WSMA} + 150.5 \text{ WSMI} - 21.22 \text{ SSW} + 14.24 \text{ RZSW}$	55.40 %	51.00 %	43.87 %	213.60	235.81	40.32 %	<0.001
Tanhril	Fruit formation	$-3.26 - 0.579 \text{ TM} + 0.424 \text{ TMMA} + 0.0689 \text{ RH} - 0.0518 \text{ PR}$	60.95 %	59.11 %	56.51 %	232.65	246.63	54.55 %	<0.001
Sairang	Fruit formation	$137.4 - 0.2076 \text{ TMMI} - 1.351 \text{ PS} - 0.1948 \text{ PAR}$	45.67 %	43.78 %	39.94 %	232.80	244.59	36.18 %	<0.001
Tanhril	Matured fruit	$7.04 + 0.2805 \text{ TM} - 0.194 \text{ TMMA} - 0.0279 \text{ RH} - 3.416 \text{ WS} + 9.78 \text{ SSW} - 18.44 \text{ RZSW} + 0.2013 \text{ PAR}$	94.43 %	93.96 %	93.28 %	73.43	93.68	92.78 %	<0.001
Sairang	Matured fruit	$-1.584 + 0.632 \text{ TM} - 0.436 \text{ TMMI} - 0.2023 \text{ QV} - 5.019 \text{ WS} + 75.8 \text{ WSMI} + 9.63 \text{ SSW} - 10.73 \text{ RZSW} + 0.0860 \text{ PAR}$	95.40 %	94.95 %	94.25 %	60.85	83.06	94.08 %	<0.001

For Tanhril, the variables TM, TMMA, RH, and PR explained 54.55% of the variation in fruit formation. While in Sairang, TMMI, PS, and PAR explained 36.18% of the variability in fruit formation. The optimal model for fruit formation, according to AIC values, was: Fruit formation = $-3.26 - 0.579 \text{ TM} + 0.424 \text{ TMMA} + 0.0689 \text{ RH} - 0.0518 \text{ PR}$ (Table 5.6.). For Tanhril, TM, TMMA, RH, WS, SSW, RZSW, and PAR explained 92.78% of the variability in matured fruit. For Sairang, TM, TMMI, QV, WS, WSMI, SSW, RZSW, and PAR explained 94.08% of the variation in matured fruit. The best-fit model for matured fruit, as determined by AIC values, was: Matured fruit = $-1.584 + 0.632 \text{ TM} - 0.436 \text{ TMMI} - 0.2023 \text{ QV} - 5.019 \text{ WS} + 75.8 \text{ WSMI} + 9.63 \text{ SSW} - 10.73 \text{ RZSW} + 0.0860 \text{ PAR}$ (Table 5.6.). These models highlighted the significant influence of various environmental factors on the different stages of reproductive phenology. The identification of these key factors are crucial for improving predictions of plant reproductive outcome and understanding the underlying mechanisms driving phenological shifts.

5.1.6. Stepwise multiple regression analysis of different reproductive phenological events and environmental parameters

In the analysis for Tanhril, variables including PR, PS, RZSW, Fruit formation, and matured fruit were automatically selected. These parameters collectively accounted for 43.77% of the variation in the flowering stage. In contrast, for Sairang, variables such as RH, WS, WSMA, RZSW, and fruit formation explained 50.06% of the variability in flowering. Based on the AIC values, the optimal model for predicting flowering was: Flowering = $-2.588 + 0.0921 \text{ RH} + 16.71 \text{ WS} - 6.04 \text{ WSMA} - 6.54 \text{ RZSW} - 0.2723 \text{ Fruit formation}$ (Table 5.7.). For the Tanhril, the variables TM, TMMA, TMMI, QV, RH, PR, WS, and matured fruit together explained 62.39% of the variability in finished flowering. For the Sairang, TM, WSMA, WSMI, SSW, PAR, flowering, fruit formation, and matured fruit accounted for 46.88% of the variability in finished flowering. The best-fit model for finished flowering, determined by AIC values, was: Finished flowering = $6.80 - 0.1736 \text{ TM} - 2.549 \text{ WSMA} + 153.9 \text{ WSMI} - 3.35 \text{ SSW} + 0.176 \text{ PAR} + 0.1944 \text{ Flowering} + 0.3251 \text{ Fruit formation} - 0.708 \text{ Matured fruit}$ (Table 5.7.).

Table 5.7. Tabulated results of multiple linear regression of different reproductive phenological events and environmental parameters studied.

Site	Dependent variable	Regression equation	Observed R^2	Adjusted R^2	Predicted R^2	AIC	BIC	Validation test R^2	p-value
Tanhril	Flowering	$-176.0 - 0.1289 \text{ PR} + 1.764 \text{ PS} + 11.07 \text{ RZSW} - 0.222 \text{ Fruit formation} + 0.470 \text{ Matured fruit}$	51.67 %	48.80 %	43.81 %	267.96	284.09	43.77 %	<0.001
Sairang	Flowering	$-2.588 + 0.0921 \text{ RH} + 16.71 \text{ WS} - 6.04 \text{ WSMA} - 6.54 \text{ RZSW} - 0.2723 \text{ Fruit formation}$	55.58 %	52.93 %	49.84 %	234.18	250.31	50.06 %	<0.001
Tanhril	Finished flowering	$-29.06 - 1.320 \text{ TM} + 1.194 \text{ TMMA} + 1.078 \text{ TMMI} - 1.189 \text{ QV} + 0.2983 \text{ RH} - 0.0549 \text{ PR} + 4.92 \text{ WS} - 0.423 \text{ Matured fruit}$	70.38 %	67.46 %	64.45 %	228.53	250.74	62.39 %	<0.001
Sairang	Finished flowering	$6.80 - 0.1736 \text{ TM} - 2.549 \text{ WSMA} + 153.9 \text{ WSMI} - 3.35 \text{ SSW} + 0.176 \text{ PAR} + 0.1944 \text{ Flowering} + 0.3251 \text{ Fruit formation} - 0.708 \text{ Matured fruit}$	58.65 %	54.57 %	45.33 %	206.79	229.01	46.88 %	<0.001
Tanhril	Fruit formation	$6.13 - 0.2019 \text{ TM} + 8.23 \text{ WS} - 5.27 \text{ WSMA} - 0.1069 \text{ Flowering} + 0.2843 \text{ Finished flowering}$	64.14 %	62.00 %	57.68 %	227.34	243.48	56.27 %	<0.001
Sairang	Fruit formation	$80.9 - 0.1549 \text{ TMMI} - 0.780 \text{ PS} - 0.2102 \text{ PAR} - 0.3002 \text{ Flowering} + 0.3587 \text{ Finished flowering}$	58.15 %	55.65 %	49.69 %	213.98	230.11	49.44 %	<0.001
Tanhril	Matured fruit	$2.174 + 0.2054 \text{ TM} - 0.1360 \text{ QV} - 3.133 \text{ WS} + 12.55 \text{ SSW} - 19.22 \text{ RZSW} + 0.1472 \text{ PAR} - 0.1236 \text{ Finished flowering}$	94.87 %	94.43 %	93.88 %	66.12	86.37	93.66 %	<0.001
Sairang	Matured fruit	$0.36 + 0.436 \text{ TM} - 0.399 \text{ TMMI} - 3.697 \text{ WS} + 121.9 \text{ WSMI} - 3.124 \text{ RZSW} + 0.0935 \text{ PAR} + 0.0686 \text{ Flowering} - 0.1214 \text{ Finished flowering}$	95.24 %	94.77 %	94.17 %	63.93	86.15	93.74 %	<0.001

For Tanhril, variables including TM, WS, WSMA, flowering, and finished flowering explained 56.27% of the variability in fruit formation. In Sairang, TMMI, PS, PAR, flowering, and finished flowering accounted for 49.44% of the variability in fruit formation. The best-fit model for predicting fruit formation, based on AIC values, was: Fruit formation = $80.9 - 0.1549 \text{ TMMI} - 0.780 \text{ PS} - 0.2102 \text{ PAR} - 0.3002 \text{ Flowering} + 0.3587 \text{ Finished flowering}$ (Table 5.7.). For Tanhril, TM, QV, WS, SSW, RZSW, PAR, and finished flowering explained 93.66% of the variability in matured fruit. In Sairang, TM, TMMI, WS, WSMI, RZSW, PAR, flowering, and finished flowering accounted for 93.74% of the variability in matured fruit. The best-fit model for predicting matured fruit, based on AIC values, was: Matured fruit = $0.36 + 0.436 \text{ TM} - 0.399 \text{ TMMI} - 3.697 \text{ WS} + 121.9 \text{ WSMI} - 3.124 \text{ RZSW} + 0.0935 \text{ PAR} + 0.0686 \text{ Flowering} - 0.1214 \text{ Finished flowering}$ (Table 5.7.).

5.2. Floral biology

The inflorescence of *P. timoriana* is characterized by a complex, multi-zonal structure composed of different types of flowers arranged in a hanging, pear-shaped capitulum. At the base of the inflorescence are hermaphrodite flowers, typically yellowish or white, each with a well-developed calyx and tubular corolla (Figure 5.3.). These flowers are responsible for sexual reproduction and seed formation. Immediately above this fertile zone lies a region of specialized nectar producing flowers, which, while not involved in reproduction, play a significant role in attracting pollinators like bats and insects through the production of copious nectar (Figure 5.3.). The apex portion of the capitulum comprises sterile or staminoidal flowers, often exhibiting elongated, whitish staminodia that form a pronounced fringe (Figure 5.3.). These structures, although non-reproductive, may provide structural support and serve as visual or physical cues to further facilitate pollinator visitation. This intricate organization within the inflorescence ensures both efficient pollinator attraction and successful reproduction, highlighting the evolutionary adaptations of *P. timoriana* for maximizing reproductive success in its ecological context.

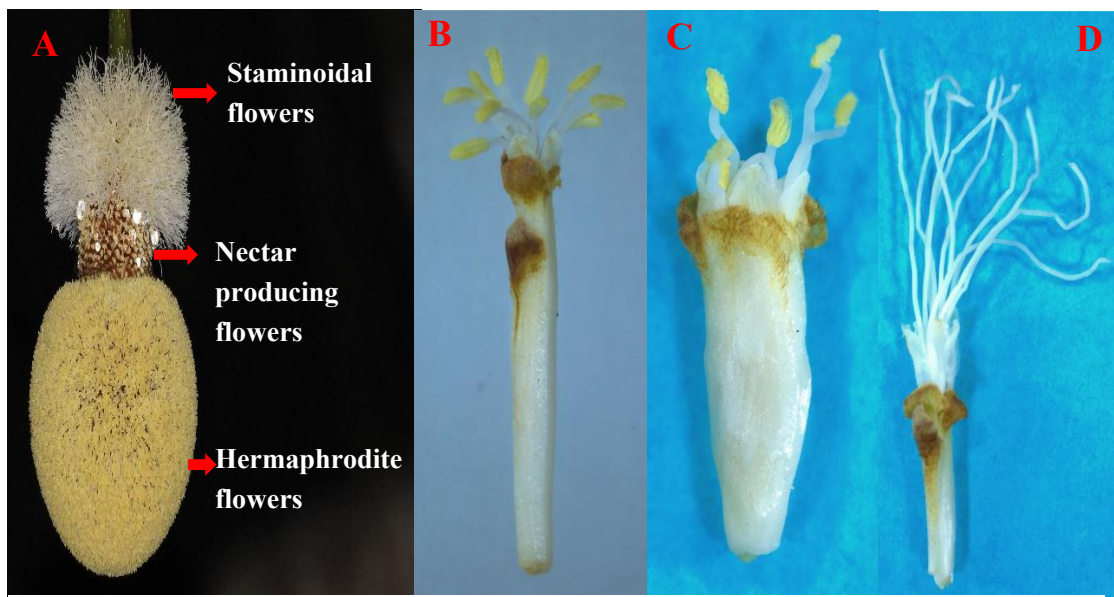


Figure 5.3. Types of *P. timoriana* flower: A= *P. timoriana* inflorescence, B= Hermaphrodite flower, C= Nectar producing flower, D= Staminoidal flower.

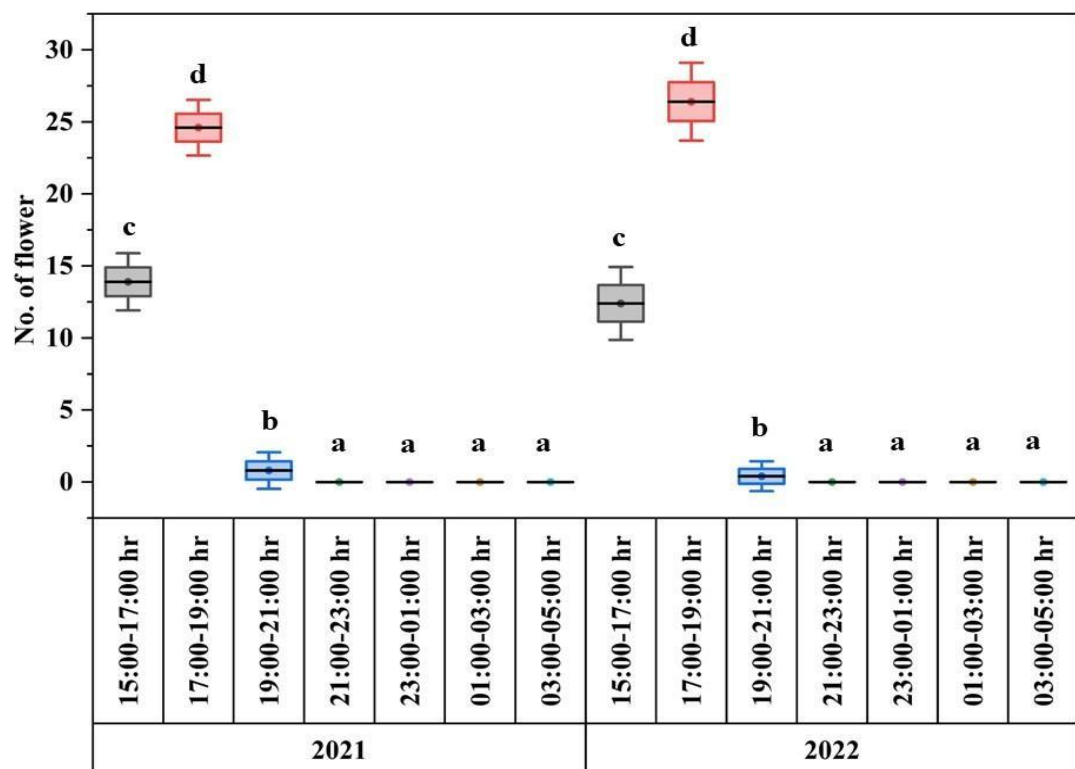


Figure 5.4. The pattern of anthesis w.r.t. time block for the year 2021 and 2022.

5.2.1. Anthesis

The figure 5.4. presents the pattern of anthesis (flower blooming) across different time blocks for the years 2021 and 2022. In both years, the first noticeable anthesis occurred during the 15:00-17:00 hr time block (Figure 5.4.). The highest anthesis was recorded during the 17:00-19:00 hr time block, marking the peak of anthesis. This period exhibited a marked enhancement in blooming relative to all other time intervals, emphasizing the late afternoon and early evening as the peak times for blooming activity. After the peak at 17:00-19:00 hr, there was a marked decline in blooming, with a significant drop between 19:00-21:00 hr. Furthermore, no additional anthesis was observed from 21:00-05:00 hr, with the time blocks from 21:00 hr to 05:00 hr showing no further blooming activity, as indicated by the "a" label, which denotes no significant difference during this period (Figure 5.4.). The pattern in 2022 largely mirrored that of 2021, with the first bloom occurring during 15:00-17:00 hr and the peak anthesis during 17:00-19:00 hr. However, the anthesis during the 17:00-19:00 hr period in 2022 was slightly lower than that of 2021. Similarly, there was no anthesis observed between 21:00 hr and 05:00 hr, as seen in 2021 (Figure 5.4.).

The initial visual sign of anthesis was the gradual swelling and expansion of flower buds, beginning around 15:45 hr. Once the petals fully opened, the reproductive organs, including the stamens and pistils, were exposed (Figure 5.5.). Anthesis in *P. timoriana* was characterized by rapid and synchronized blooming, with most flowers on a tree opening within a short window of approximately four to five hours. This synchronization likely maximizes pollination efficiency by concentrating pollinator activity during a specific time period. Observations revealed that 60% of the total marked flowers reached full anthesis between 17:00-19:00 hr, establishing this period as the peak phase of anthesis. Flowers that bloomed during this peak phase remained open throughout the night and for the following one to two days, offering ample opportunities for both diurnal and nocturnal pollinators to engage in pollination.



Figure 5.5. Different stages of anthesis of *P. timoriana* till fruits formation.

5.2.2. Pattern of anther dehiscence

The pattern of anther dehiscence in *P. timoriana* was closely linked to the timing of anthesis. In 2021, the first signs of anther dehiscence were observed during the 15:00-17:00 hr time block, marking the onset of pollen release. The highest number of dehiscent anthers occurred during the 17:00-19:00 hr block, denoted by the "d" label, indicating a significant increase in dehiscence compared to earlier time points (Figure 5.6.). This period, coinciding with peak anthesis, represented the highest level of pollen release, which was significantly different from all other time blocks. Following the peak, a notable decrease in anther dehiscence was observed, with a substantial reduction in the number of dehiscent anthers by the 19:00-21:00 hr period. A complete cessation of dehiscence was noted from 23:00-05:00 hr, where no pollen release occurred. The absence of dehiscent anthers during these hours was marked with the "a" label, signifying no significant difference in these time blocks (Figure 5.6.).

In 2022, the pattern of anther dehiscence followed a similar trajectory, with the initial dehiscence occurring during the 15:00-17:00 hr block, although the mean number of dehiscent anthers was slightly lower compared to 2021. As in the previous year, the highest dehiscence was recorded during the 17:00-19:00 hr block, with a clear cessation of dehiscence from 23:00-05:00 hr, consistent with the 2021 results (Figure 5.6.). The dehiscence process was found to be highly synchronized across the flowers (Figure 5.7.), with most anthers releasing their pollen between 17:00-19:00 hr (Figure 5.6.). During this peak period, approximately 70% of the anthers had fully dehisced, with visible pollen on the flower surfaces, ready for transfer by pollinators. The dehiscence followed a longitudinal pattern, where the anther lobes split along their length, exposing the pollen grains (Figure 5.7.). Initially, small cracks were observed along the anther lobes, which progressively widened, allowing for the release of pollen. This release was continuous over a four-hour period, ensuring optimal conditions for pollination. Notably, anther dehiscence was typically completed before midnight, with little to no pollen remaining in the anthers by the following afternoon. As anther dehiscence occurred prior to the maturation of the stigma, a slight protandry was observed in *P. timoriana*, with pollen release preceding stigma receptivity. This

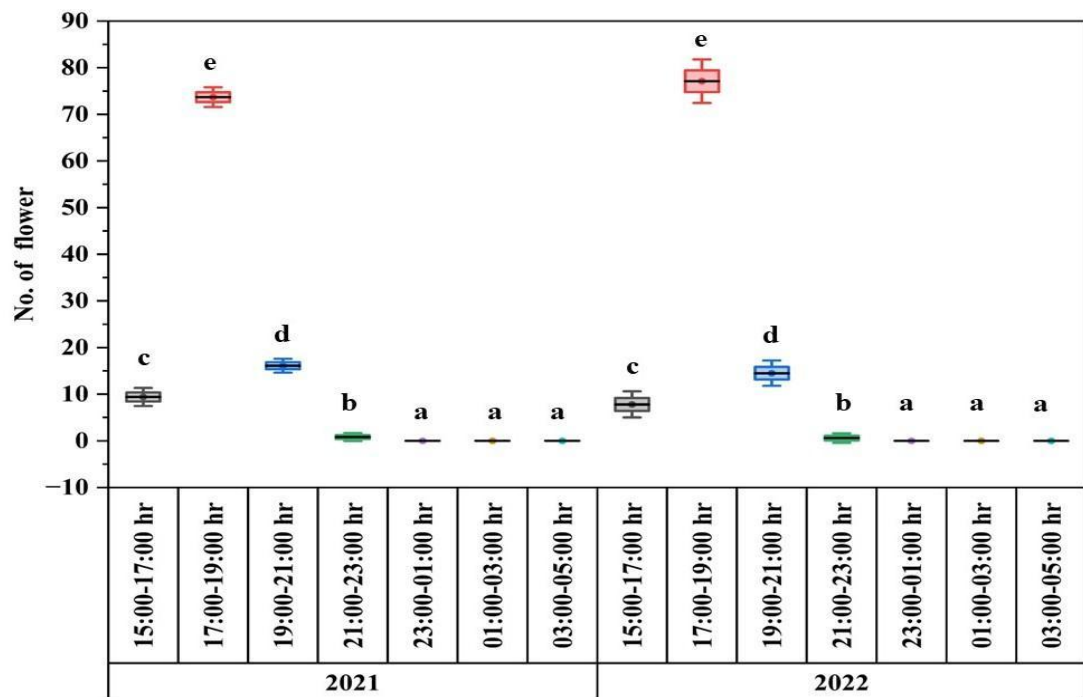


Figure 5.6. The pattern of anther dehiscence w.r.t. time block for the year 2021 and 2022.

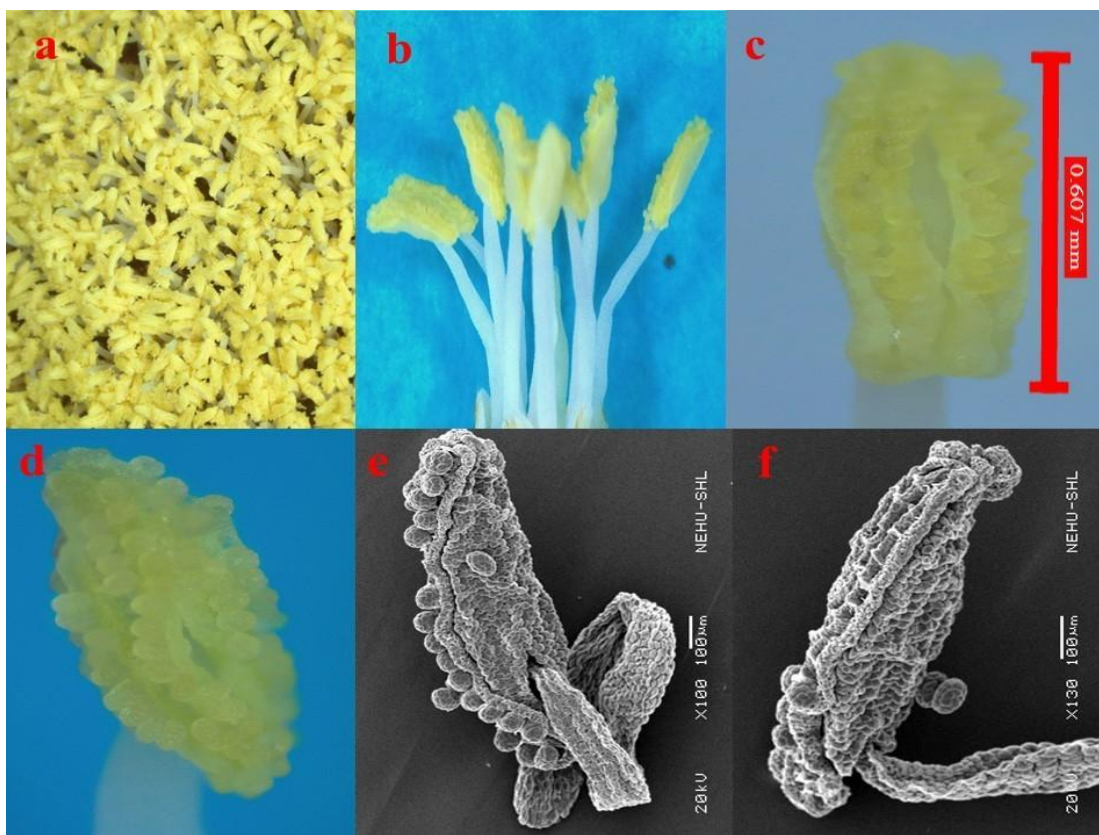


Figure 5.7. a, b= anther dehiscence; c, d= longitudinal view of fully open anther; e, f= scanning electron micrograph image of fully open anther along with polyad pollen grains on the anther surface (Scale=100 μ m).

temporal separation between anther dehiscence and stigma maturation is significant for the species' reproductive strategy, promoting effective cross-pollination and ensuring the synchronization of reproductive events.

5.2.3. Stigma receptivity

The temporal pattern of stigma receptivity in *P. timoriana* was assessed through peroxidase activity assays, which provide insight into the enzymatic changes occurring throughout the flowering period. Peroxidase activity was measured by the presence of bubbles formed upon immersion of stigmas in hydrogen peroxide, reflecting the stigma's receptivity during anthesis. In 2021, stigma receptivity was first detected during the 15:00-17:00 hr time block, although the level of activity at this time was minimal, marking the lowest receptivity observed across the entire flowering period (Figure 5.8.). A significant increase in peroxidase activity was noted during the 17:00-19:00 hr period, which represented the first substantial rise in enzymatic activity. This increase continued through the 19:00-21:00 hr block, reaching its highest point during the 21:00-23:00 hr time block, when peroxidase activity was at its peak. Notably, the peak in enzymatic activity was maintained through the 01:00-03:00 hr period, indicating that stigma receptivity remained high through the night (Figure 5.8.). However, by the 03:00-05:00 hr block, a slight decline in peroxidase activity was observed, though it remained significantly higher than the initial 15:00-17:00 hr period (Figure 5.8.). This pattern of peroxidase activity was consistent across both 2021 and 2022, confirming the dynamic and time-dependent nature of stigma receptivity in this species.

The esterase activity assay also revealed a time-dependent receptivity pattern, with varying staining intensities corresponding to different levels of enzyme activity. Stigmas collected between 19:00-01:00 hr exhibited the highest esterase activity, with most samples showing strong positive reactions (+++), indicating high levels of esterase enzymes associated with peak stigma receptivity (Figure 5.9.). Conversely, stigmas collected after midnight, early the following morning, and during the late afternoon showed weaker staining, with most samples categorized as weak (+), suggesting a decrease in receptivity. These findings align with the results from the

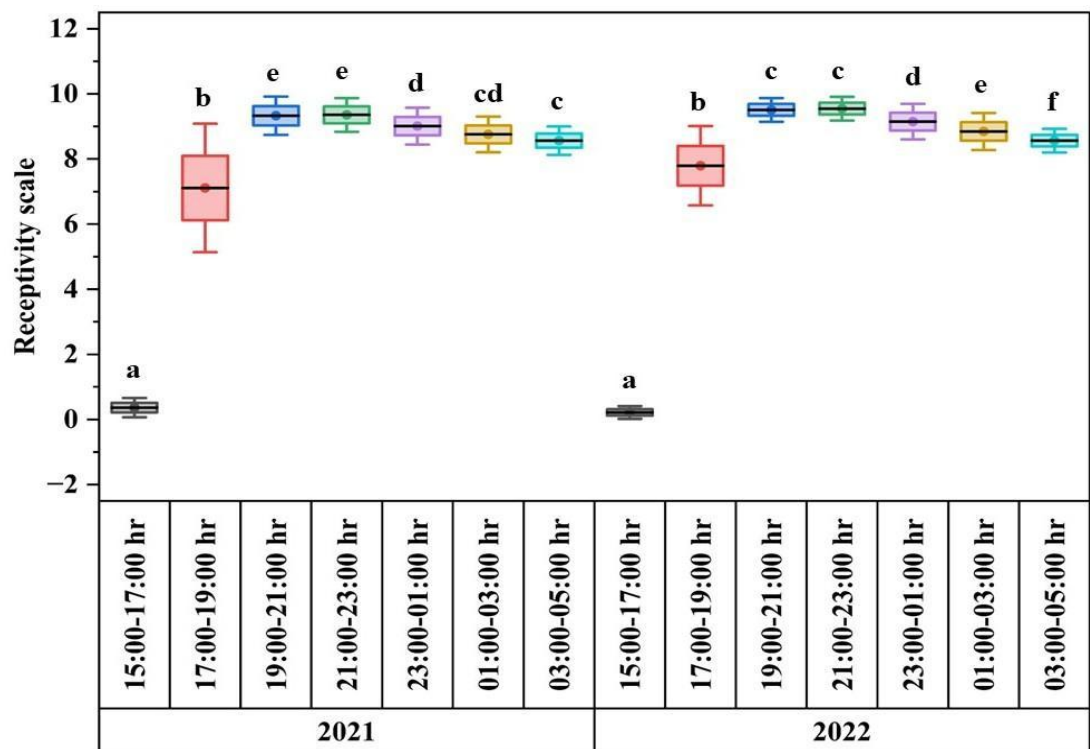


Figure 5.8. The pattern of stigma receptivity w.r.t. time block for the year 2021 and 2022.

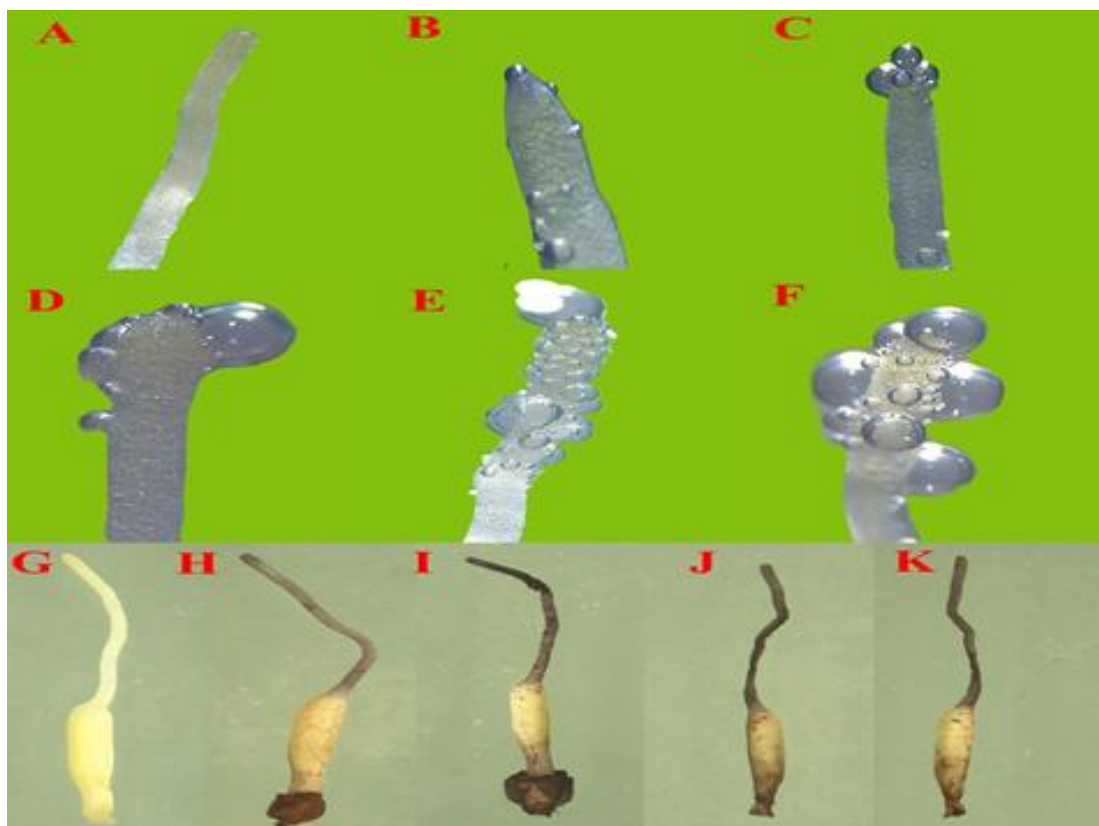


Figure 5.9. Different stages of stigma receptivity. A-F= stigma receptivity test by using peroxidase-based hydrogen peroxide test. G-K= stigma receptivity test by using α -Naphthyl acetate as a substrate.

peroxidase assay, indicating that both enzymatic activities followed similar temporal patterns, with high receptivity observed in the evening and early night, and lower activity in the early morning and late afternoon.

5.2.4. Correlation of floral biology parameters with climatic variables

The Spearman's rank correlation analysis conducted in this study aimed to explore the relationships between floral biology parameters namely stigma receptivity, anther dehiscence, and anthesis and various environmental factors for the years 2021 and 2022. In the year 2021, the analysis revealed significant correlations between time and floral parameters, where time (T) exhibited a moderate positive correlation with stigma receptivity ($r_s = 0.346^{**}$, $p < 0.01$) and strong negative correlations with anther dehiscence ($r_s = -0.834^{**}$, $p < 0.01$) and anthesis ($r_s = -0.827^{**}$, $p < 0.01$) (Table 5.8.). Temperature at 2 meters (TM) was strongly associated with anther dehiscence ($r_s = 0.773^{**}$, $p < 0.01$) and anthesis ($r_s = 0.793^{**}$, $p < 0.01$), whereas it negatively impacted stigma receptivity ($r_s = -0.358^{**}$, $p < 0.01$) (Table 5.8.). Moreover, relative humidity (RH) exhibited a positive correlation with stigma receptivity ($r_s = 0.438^{**}$, $p < 0.01$) but negatively influenced both anther dehiscence ($r_s = -0.486^{**}$, $p < 0.01$) and anthesis ($r_s = -0.611^{**}$, $p < 0.01$). The wind speed (WS) showed a positive relationship with stigma receptivity ($r_s = 0.586^{**}$, $p < 0.01$) but had a detrimental effect on anthesis ($r_s = -0.401^{**}$, $p < 0.01$) (Table 5.8.). In 2022, similar patterns emerged, where temperature at 2 meters (TM) showed a negative correlation with stigma receptivity ($r_s = -0.382^{**}$, $p < 0.01$), while demonstrating positive associations with both anther dehiscence ($r_s = 0.779^{**}$, $p < 0.01$) and anthesis ($r_s = 0.764^{**}$, $p < 0.01$). Time (T) had a significant positive correlation with stigma receptivity ($r_s = 0.321^{**}$, $p < 0.01$) yet negatively impacted both anther dehiscence ($r_s = -0.820^{**}$, $p < 0.01$) and anthesis ($r_s = -0.794^{**}$, $p < 0.01$). Further analysis showed that wet bulb temperature (TWET) exhibited negative correlations with stigma receptivity ($r_s = -0.375^{**}$, $p < 0.01$) but positively correlated with both anther dehiscence ($r_s = 0.785^{**}$, $p < 0.01$) and anthesis ($r_s = 0.768^{**}$, $p < 0.01$) (Table 5.9.). Specific humidity (QV) also had a negative effect on stigma receptivity ($r_s = -0.239^*$, $p < 0.05$) but positively impacted both anther dehiscence ($r_s = 0.780^{**}$, $p < 0.01$) and anthesis ($r_s = 0.688^{**}$,

Table 5.8. Spearman's rank correlation analysis between different floral biology parameters and environmental parameters studied for the year 2021.

	Stigma receptivity		Anther dehiscence		Anthesis	
	r_s	p	r_s	p	r_s	p
T	0.346**	0.003	-0.834**	0.000	-0.827**	0.000
TM	-0.358**	0.002	0.773**	0.000	0.793**	0.000
TDEW	-0.226	0.060	0.836**	0.000	0.772**	0.000
TWET	-0.346**	0.003	0.789**	0.000	0.798**	0.000
QV	-0.236*	0.050	0.833**	0.000	0.773**	0.000
RH	0.438**	0.000	-0.486**	0.000	-0.611**	0.000
PR	-0.363**	0.002	-0.004	0.975	0.191	0.114
WS	0.586**	0.000	-0.230	0.055	-0.401**	0.001
Stigma receptivity	1	-	-0.219	0.068	-0.551**	0.000
Anther dehiscence	-0.219	0.068	1	-	0.847**	0.000
Anthesis	-0.551**	0.000	0.847**	0.000	1.000**	-

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

$p < 0.01$) . Relative humidity (RH) demonstrated a positive correlation with stigma receptivity ($r_s = 0.327^{**}$, $p < 0.01$), while negatively affecting both anther dehiscence ($r_s = -0.583^{**}$, $p < 0.01$) and anthesis ($r_s = -0.594^{**}$, $p < 0.01$) (Table 5.9.). Finally, wind speed (WS) was significantly associated with stigma receptivity ($r_s = 0.622^{**}$, $p < 0.01$) but negatively impacted both anther dehiscence ($r_s = -0.260^*$, $p < 0.05$) and anthesis ($r_s = -0.502^{**}$, $p < 0.01$) (Table 5.9.). These findings indicate that environmental factors, particularly temperature, humidity, and wind speed, play a significant role in floral development, with both direct and indirect effects on floral parameters. This study provides a deeper understanding of how environmental conditions influence plant reproductive processes and offers a foundation for future research aimed at optimizing agricultural practices, particularly in the context of changing climatic conditions.

5.2.5. Stepwise regression modelling of floral biology parameters w.r.t. climatic variables

Regression models were generated for the three floral biology parameters: anthesis, anther dehiscence, and stigma receptivity with the inclusion of all the selected climatic variables. The performance metrics i.e., observed R^2 , adjusted R^2 , predicted R^2 , and validation test R^2 were calculated for the three regression models of anthesis, anther dehiscence, and stigma receptivity (Table 5.10.). The p-values for regression models were less than 0.001, signifying that the models provide a good fit for the data (Table 5.10.). The equations for regression models are:

$$\text{Anthesis} = 11.552 - 1.3643 \text{ Stigma receptivity} + 0.30036 \text{ Anther dehiscence} \quad (1)$$

$$\text{Anther dehiscence} = -49.91 + 4.523 \text{ Stigma receptivity} + 3.1509 \text{ Anthesis} + 0.584 \text{ Temp.} \quad (2)$$

$$\text{Stigma receptivity} = 2.14 + 0.1622 \text{ Anther dehiscence} - 0.5230 \text{ Anthesis} - 0.1309 \text{ Temp.} + 0.0887 \text{ RH} + 1.467 \text{ Wind speed} \quad (3)$$

Table 5.9. Spearman's rank correlation analysis between different floral biology parameters and environmental parameters studied for the year 2022.

	Stigma receptivity		Anther dehiscence		Anthesis	
	r_s	p	r_s	p	r_s	p
T	0.321**	0.007	- 0.820**	0.000	- 0.794**	0.000
TM	- 0.382**	0.001	0.779**	0.000	0.764**	0.000
TDEW	- 0.215	0.074	0.793**	0.000	0.691**	0.000
TWET	- 0.375**	0.001	0.785**	0.000	0.768**	0.000
QV	- 0.239*	0.046	0.780**	0.000	0.688**	0.000
RH	0.327**	0.006	- 0.583**	0.000	- 0.594**	0.000
PR	0.067	0.580	- 0.142	0.239	- 0.043	0.725
WS	0.622**	0.000	- 0.260*	0.030	- 0.502**	0.000
Stigma receptivity	1	-	- 0.224	0.063	- 0.653**	0.000
Anther dehiscence	- 0.224	0.063	1	-	0.782**	0.000
Anthesis	- 0.653**	0.000	0.782**	0.000	1.000**	-

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Table 5.10. Regression models of floral biology parameters with climatic variables.

Floral biology parameters	Regression equation	Observed R^2	Adjusted R^2	Predicted R^2	Validation test R^2	p-value
Anthesis	11.552 - 1.3643 SR + 0.30036 AD	97.30 %	97.22 %	97.03 %	96.96 %	<0.001
Anther dehiscence	-49.91 + 4.523 SR+ 3.1509 A + 0.584 T	96.35 %	96.19 %	95.90 %	95.85 %	<0.001
Stigma receptivity	2.14 + 0.1622 AD - 0.5230 A - 0.1309 T + 0.0887 RH + 1.467 WS	91.52 %	90.86 %	89.65 %	89.50 %	<0.001

For anthesis, parameters such as stigma receptivity and anther dehiscence were auto selected in the analysis. Together, they explained 97.22 % variability. The combined influence of stigma receptivity, anthesis, and temperature accounted for 96.35% of the variability in anther dehiscence. For stigma receptivity, the factors of anther dehiscence, anthesis, temperature, relative humidity, and wind speed collectively explained 91.52% of the variability (Table 5.10.).

5.3. Morphology of pollen in *P. timoriana*

The pollen grains of *P. timoriana* are arranged in cavitate polyads, consisting of tightly clustered individual pollen grains. Each polyad typically comprises 32 pollen grains arranged in a spherical or slightly ellipsoidal structure (Figures 5.10., 5.11.). The polyads show a clear, organized grouping of individual pollen units. The spherical or sub-spherical nature of the polyad ensures cohesion, which is a key feature for effective pollination in species that rely on animal vectors for pollen dispersal. The size of the polyads is approximately 70-90 μm in diameter. The compact spherical organization helps in maintaining the integrity of the polyad during dispersal. Individual pollen grains within the polyad have a diameter of approximately 15-20 μm . At higher magnifications (x1000, x5000, x7000), the surface of the polyads and individual grains appears slightly uneven but generally smooth. The individual pollen grains have a characteristic surface texture that lacks deep sculpturing or prominent ornamentation. No differences in exine ornamentation were observed among pollen grains within the same polyad. Additionally, there was no variation in the position or fusion of the pollen aperture, nor were there any signs of adhesion or compression between adjacent ectexines. In higher magnification close-ups, certain areas show a small central depression, possibly corresponding to an aperture, indicating the germination pore of the pollen grain (Figures 5.10., 5.11.). The depressions in the individual grains suggest a colpate or porate structure, typical of the family Fabaceae to which *P. timoriana* belongs. The polyads exhibit near-perfect symmetry, especially in the spherical forms, with each individual pollen grain tightly packed. This packing is highly organized, with the grains arranged in polygonal shapes when viewed from

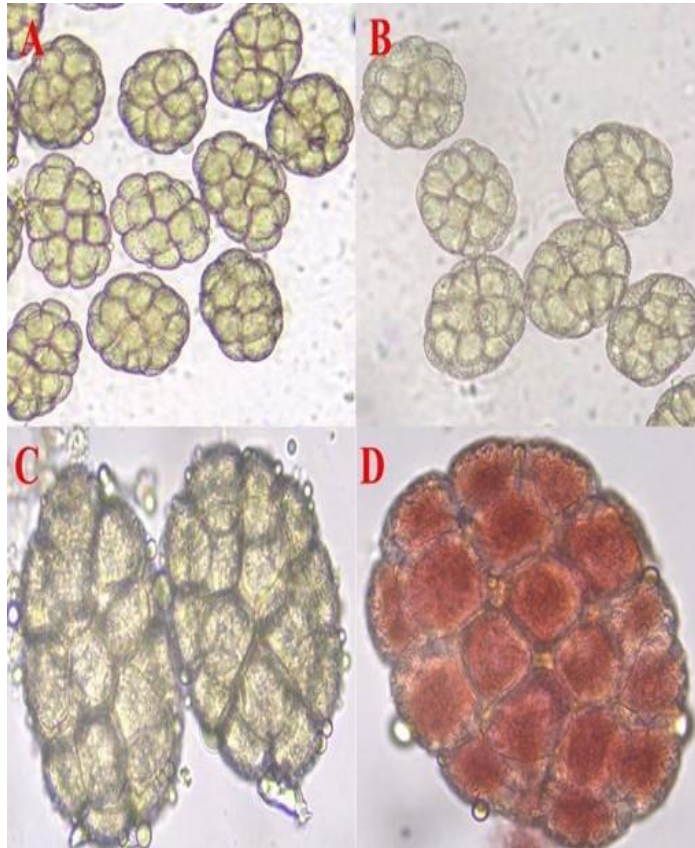


Figure 5.10. Microphotographs of light microscopy showing pollen view and sculpturing of *P. timoriana* polyad pollen grains. Scale bars: A = 10X; B = 20X; C, D = 40X

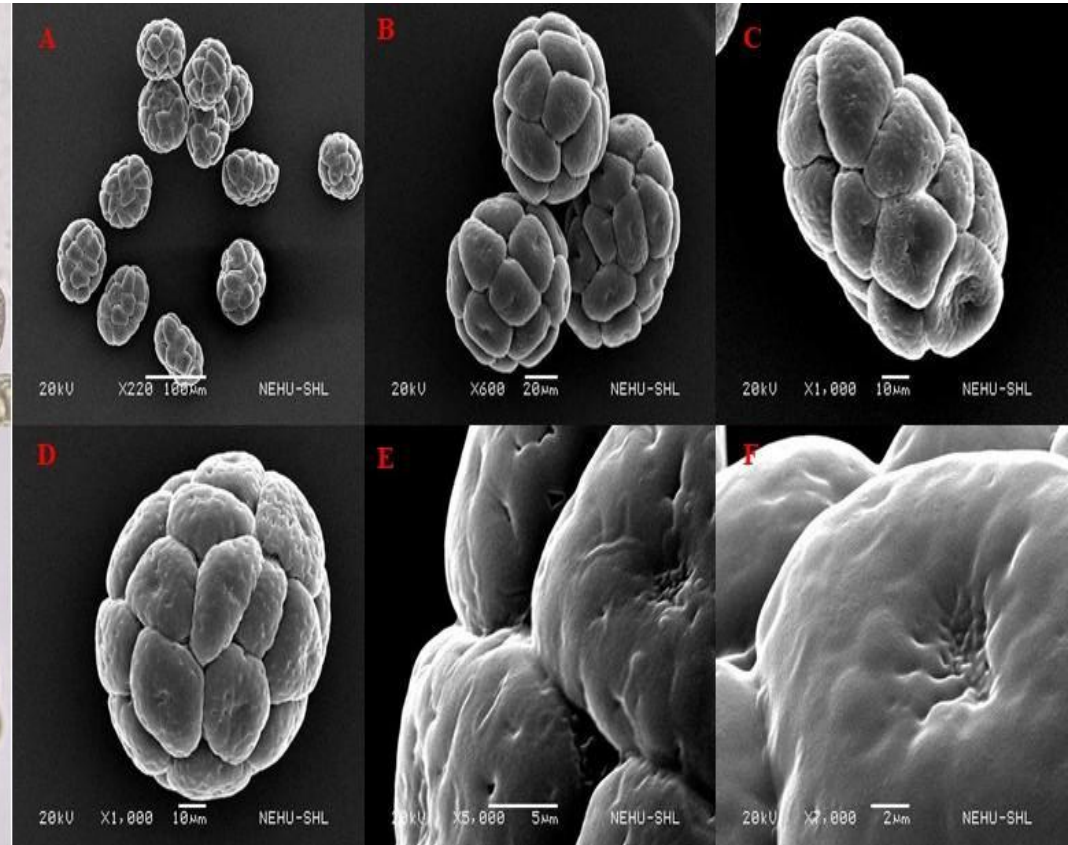


Figure 5.11. Microphotographs of scanning electron microscopy showing pollen polar and equatorial view and sculpturing of *P. timoriana* polyad pollen grains. Scale bars: A= 220 μm ; B= 600 μm ; C, D= 1000 μm ; E= 5000 μm ; F= 7000 μm .

the surface, contributing to the tessellated appearance. Some polyads display slight deviations from a perfect spherical shape, appearing more ellipsoidal.

5.4. Pollinators behaviour

Based on detailed field observations of *P. timoriana* floral visitors, the animal species recorded were grouped according to the frequency and nature of their visitation behavior. The primary group comprising: *Camponotus* spp., *Tapinoma sessile* Say, *Bombus bicoloratus* Smith, *Apis cerana indica* Fabricius, *Trigona* spp., *Vespa affinis* Linnaeus, *Phimenes flavopictus* Blanchard, *Achaea serva* Fabricius, *Agrotis infusa* Boisduval, *Ercheia cyllaria* Cramer, *Eudocima phalonia* Linnaeus, *Hulodes caranea* Cramer, *Psyrassa unicolor* Randall, *Ariadne merione* Cramer, and bats were observed to visit the flowers frequently and interact closely with the plant's reproductive structures (Figures 5.12. and 5.13.). These species were classified as pollinators due to their regular and consistent engagement with the floral organs during their visits.

In contrast, *Amsacta albistriga* Walker, *Hypersypnoides* spp., *Halyomorpha halys* Stål, mosquitoes, *Prosenia* spp., *Batocera rubus* Linnaeus, *Zosterops palpebrosus* Temminck, and *Phaneroptera falcata* Poda were observed only sporadically at the flowers of *P. timoriana* (Figures 5.14.). Their appearances were infrequent and their interactions with the flowers appeared incidental rather than purposeful or regular. As such, these species were categorized as random or occasional visitors. This classification, based on patterns of visitation frequency and behavior, allows for a clearer understanding of the diverse ecological roles of the different animals associated with *P. timoriana*, irrespective of their contribution to the plant's reproductive function.

5.4.1. Visitation frequency of *Camponotus* spp.

The visitation patterns of *Camponotus* spp. across different time blocks for the years 2021 and 2022 exhibit notable diurnal fluctuations, with significant temporal variation observed in visitation frequency. In 2021, the peak visitation occurred between 19:00 and 21:00 hours, with a mean frequency of 7.40 visits per 2 hours, followed by a notable decline during the late evening to early morning periods. Specifically, the



Figure 5.12. Pollinators of *P. timoriana* (A)



Figure 5.13. Pollinators of *P. timoriana* (B)

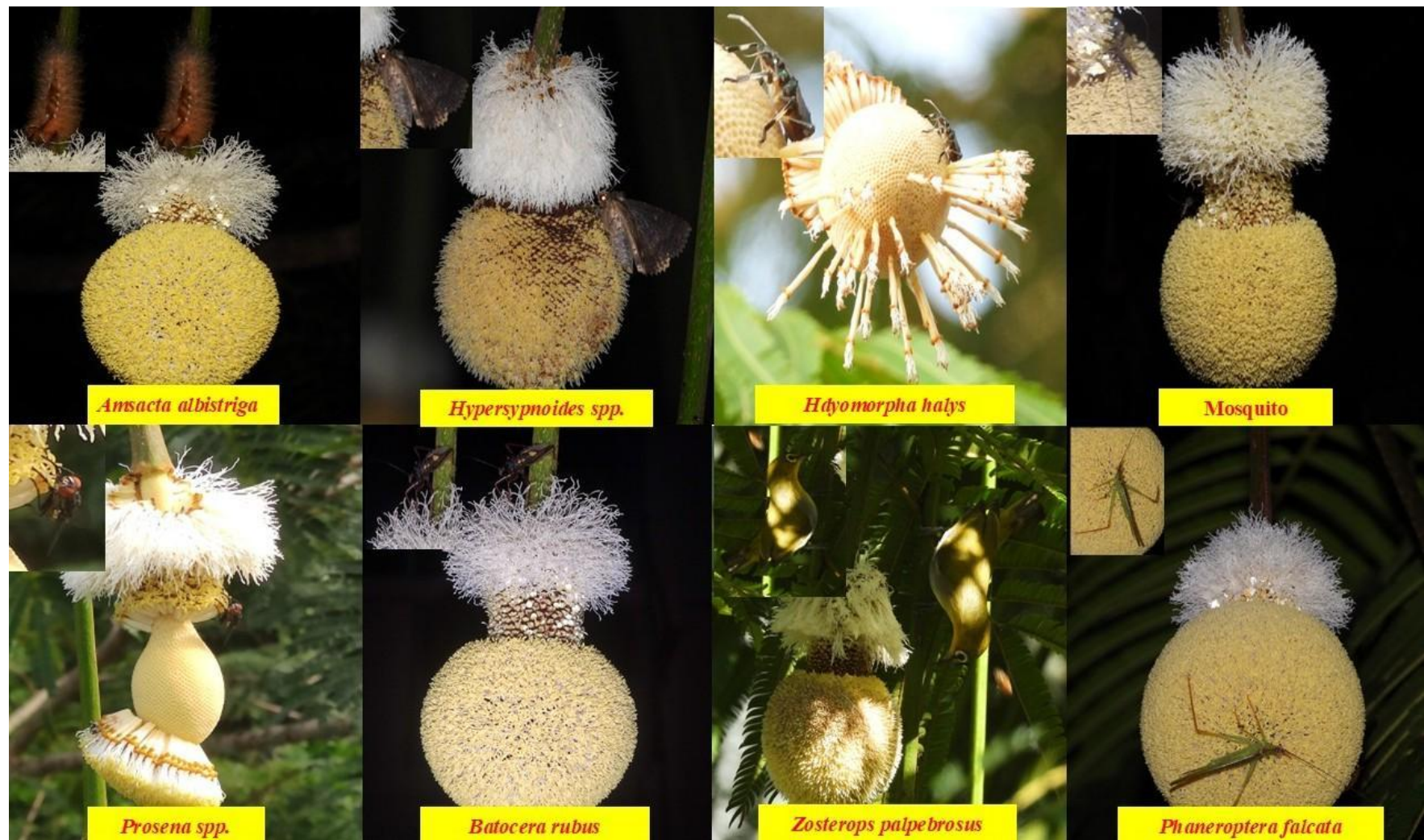


Figure 5.14. Random visitors of *P. timoriana*

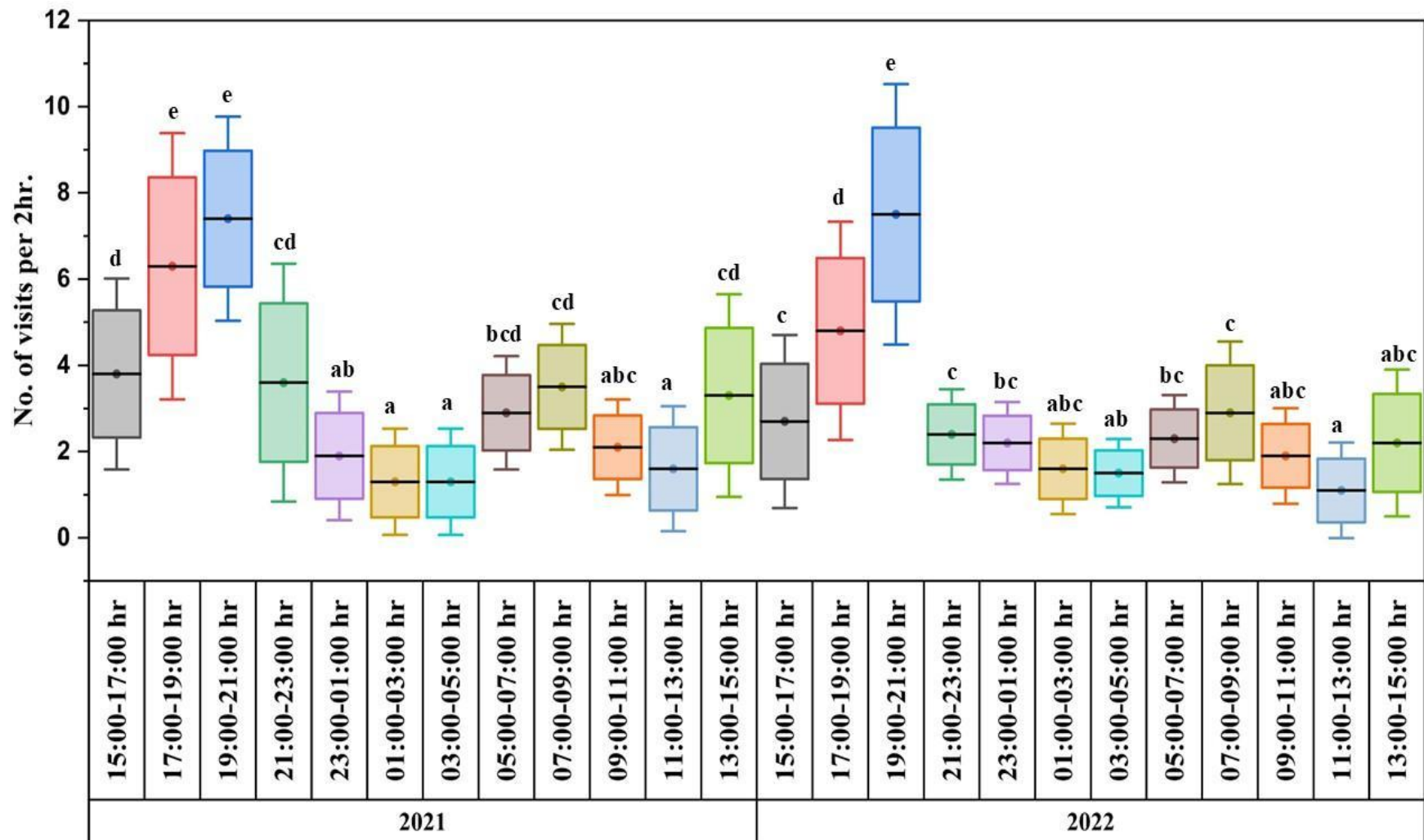


Figure 5.15. Visitation frequency of *Camponotus* spp. w.r.t. to time block for the year 2021 and 2022.

visitation frequency dropped to 1.30 visits per 2 hrs. between 01:00-03:00 hrs. (Figure 5.15.). In 2022, the highest visitation frequency was observed between 19:00 and 21:00 hours which was slightly higher at 7.50 visits per 2 hours comparing with 2021, though visitation throughout the rest of the day appeared generally reduced compared to 2021. The data suggests a consistent pattern where the visitation frequency decreases significantly from late evening through early morning, with the lowest visitation rates observed during the 01:00-03:00 and 03:00-05:00 hours (Figure 5.15.). Additionally, the standard deviations for both years suggest considerable variability in visitation rates, particularly during late afternoon and evening hours, which might indicate environmental or ecological factors influencing the behavior of *Camponotus* spp.. These temporal shifts in visitation frequency could be attributed to a variety of factors, such as changes in environmental conditions, food availability, or interspecific interactions, thus highlighting the need for further investigation into the underlying causes of such variations. The overall trends across both years indicate a pattern of decreased visitation in 2022 relative to 2021, which warrants further exploration into potential changes in habitat conditions or behavioral ecology that may have influenced the observed decline in visitation rates.

5.4.2. Visitation frequency of *Tapinoma sessile*

The visitation frequency of *Tapinoma sessile* across different time blocks during the years 2021 and 2022 exhibits clear temporal fluctuations, with the highest mean visitation occurring during the evening and early night periods in both years. In 2021, the peak visitation was recorded between 19:00 and 21:00 hours, with a mean of 15.60 visits per 2 hours, followed by a gradual decline as the day progressed into late night and early morning hours (Figure 5.16.). The visitation frequency dropped significantly during the 01:00-03:00 hour period, with a mean of 3.10 visits per 2 hours, and remained low throughout the early morning. Similarly, in 2022, the peak visitation occurred between 19:00 and 21:00 hours, with a mean of 13.40 visits per 2 hours, though visitation rates during this period were slightly lower compared to the previous year. The 15:00-17:00 hour block, while still relatively high, saw a decrease in visitation from 10.40 visits per 2 hours in 2021 to 8.90 visits per 2 hours in 2022.

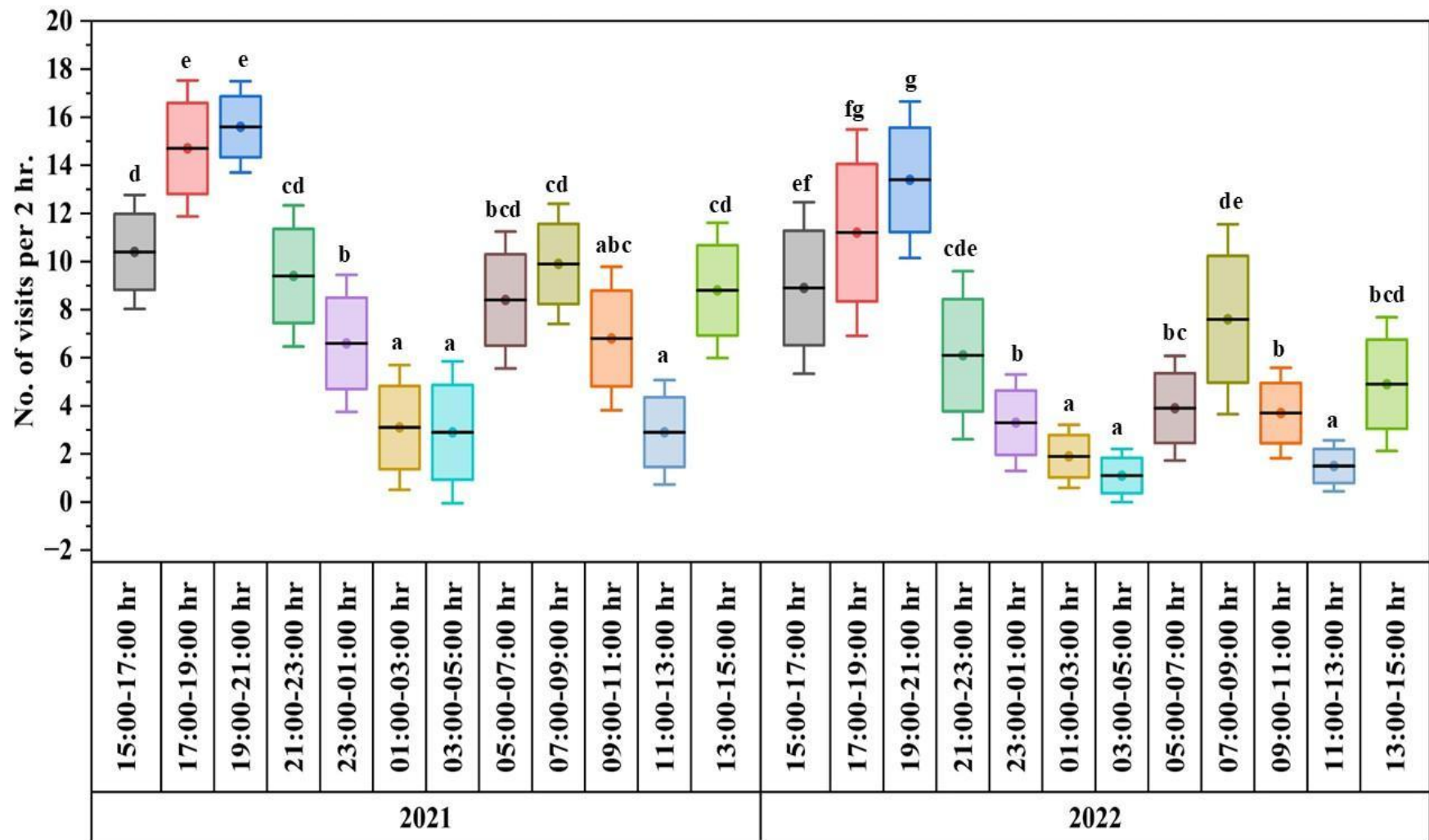


Figure 5.16. Visitation frequency of *Tapinoma sessile* w.r.t. to time block for the year 2021 and 2022.

(Figure 5.16.). The lowest visitation rates in 2022 were observed between 03:00 and 05:00 hours, where the mean visitation frequency was 1.10 visits per 2 hours. Notably, the standard deviations for visitation frequency in both years suggest some degree of variation in activity levels, with the highest variability observed during the early morning hours, especially in 2022 (Figure 5.16.). The data from both years reveal a comparable diurnal pattern of *T. sessile* activity, characterized by an evening peak and a noticeable reduction in visitation during the late-night and early-morning hours. The reduction in visitation frequency in 2022, particularly during the early morning periods, suggests possible shifts in environmental or ecological conditions that could have influenced foraging behavior. Further studies investigating the environmental factors contributing to these shifts are warranted to better understand the temporal activity patterns of *T. sessile* and the underlying ecological drivers.

5.4.3. Visitation frequency of *Bombus bicoloratus*

The visitation patterns of *Bombus bicoloratus* across different time blocks in 2021 and 2022 demonstrate a clear temporal distribution, with distinct periods of high and low activity. In 2021, the highest mean visitation frequency occurred between 05:00 and 07:00 hours, where the visitation rate was 4.50 visits per 2 hours, followed by 07:00 to 09:00 hours with a mean of 2.40 visits per 2 hours (Figure 5.17.). Other time blocks, such as 15:00 to 17:00 hours and 03:00 to 05:00 hours, showed moderate activity, with mean visitation frequencies of 2.30 and 1.40 visits per 2 hours, respectively (Figure 5.17.). However, significant inactivity was observed during the evening and night periods, as no visits were recorded between 17:00 to 03:00 hours, suggesting a marked reduction in foraging behavior during these times. The standard deviations in 2021 ranged from 0.57 to 1.18, indicating a moderate level of variation in visitation frequency across time blocks. In 2022, similar patterns were observed, with the highest visitation occurring between 05:00 and 07:00 hours (4.10 visits per 2 hours), albeit slightly lower than the previous year. Visitation frequency remained relatively low between the time periods 09:00 to 15:00, consistent with the less visitation activity seen in 2021, with no recorded visits between 17:00 and 03:00 hours (Figure 5.17.). The standard deviations in 2022 ranged from 0.42 to 1.10, reflecting less variability in

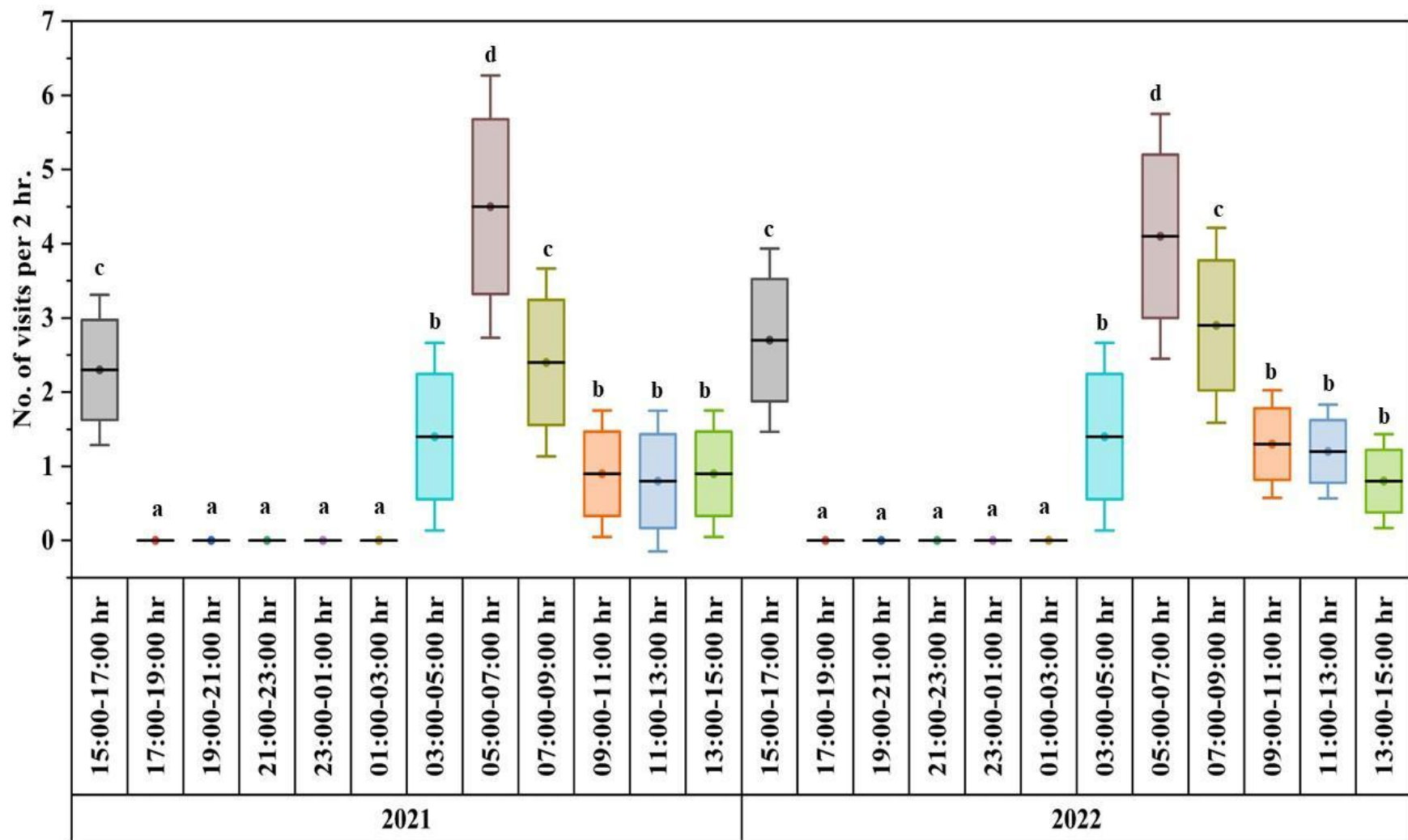


Figure 5.17. Visitation frequency of *Bombus bicoloratus* w.r.t. to time block for the year 2021 and 2022.

visitation compared to 2021, suggesting more consistent foraging behavior across time blocks. These results indicate that *B. bicoloratus* exhibits a pronounced diurnal activity pattern, with significant peaks in early morning hours and minimal activity during afternoon. The consistent patterns observed between 2021 and 2022 suggest a stable behavioral rhythm for the species, potentially influenced by environmental and ecological factors, which warrants further investigation to understand the underlying causes and their implications for the species' foraging strategies.

5.4.4. Visitation frequency of *Apis cerana indica*

The visitation patterns of *Apis cerana indica* across the years 2021 and 2022 demonstrate distinct temporal variations, with notable peaks in activity occurring during the early morning and late afternoon hours. In 2021, the highest visitation frequency was observed between 07:00 and 09:00 hours, with a mean of 47.60 visits per 2 hours, followed closely by 05:00 to 07:00 hours, where the visitation frequency was 41.60 visits per 2 hours (Figure 5.18.). These periods represent the species' peak foraging times, indicative of high activity levels during daylight morning hours. Conversely, visitation rates sharply declined during the late evening and early morning, with no recorded activity between 21:00 and 03:00 hours. Visitation resumed after 03:00 hours, but with significantly lower frequencies (19.10 visits per 2 hours) (Figure 5.18.). The pattern observed in 2021 was consistent in 2022, although the overall visitation frequencies were generally lower. In 2022, the highest visitation occurred between 07:00 and 09:00 hours (43.30 visits per 2 hours) and between 05:00 and 07:00 hours (38.20 visits per 2 hours). A slight decrease in visitation frequency was observed during the afternoon period in 2022, with 21.30 visits per 2 hours recorded between 15:00 and 17:00 hours, compared to 24.90 visits per 2 hours in 2021 (Figure 5.18.). As in 2021, *A. cerana indica* exhibited no activity between 21:00 and 03:00 hours. The standard deviations across both years indicated variability in visitation, with 2021 showing more fluctuation in activity levels compared to 2022. This temporal pattern highlights *A. cerana indica*'s preference for early morning and late afternoon foraging, with marked inactivity during the late night to early morning hours.

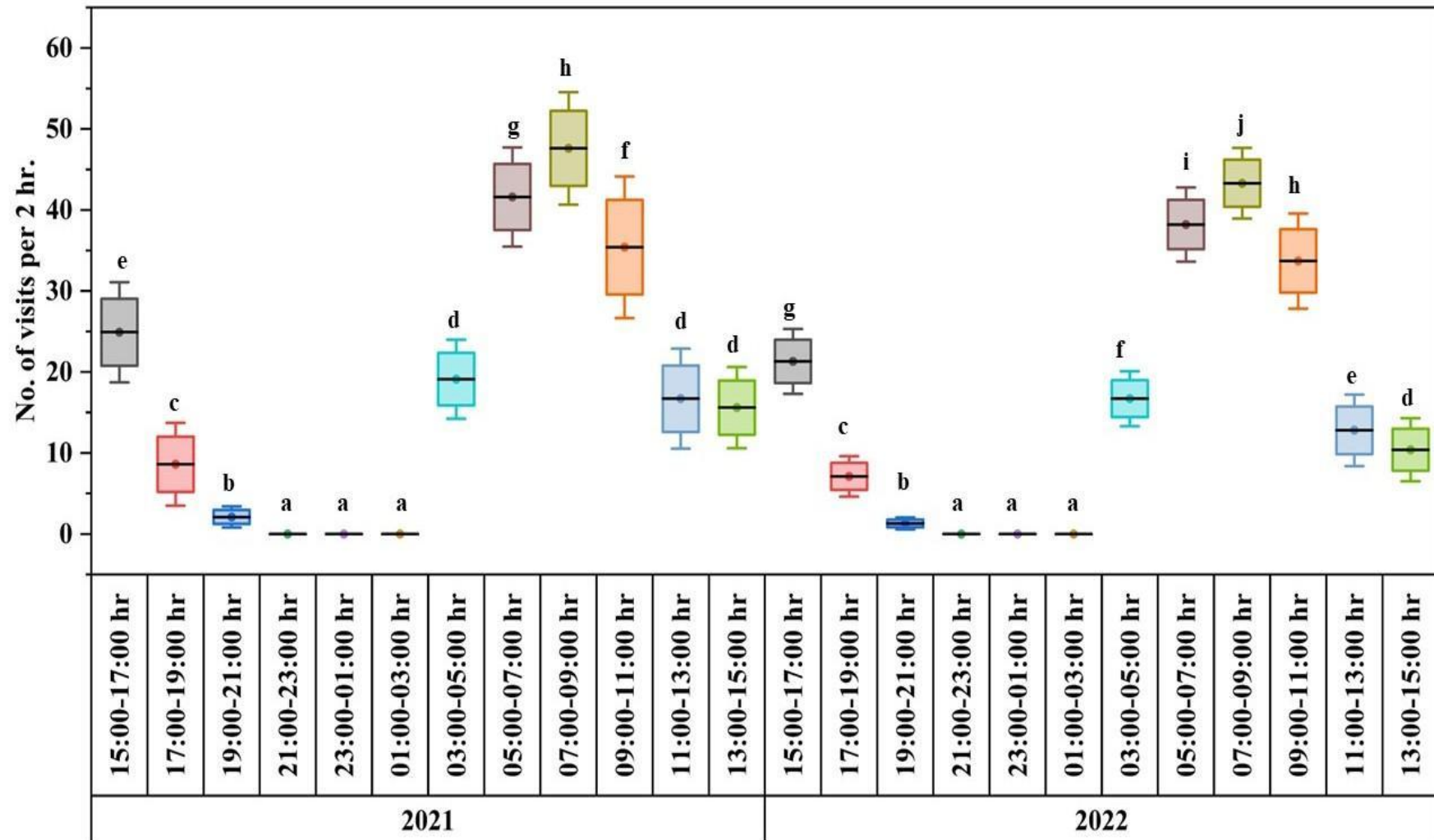


Figure 5.18. Visitation frequency of *Apis cerana indica* w.r.t. to time block for the year 2021 and 2022.

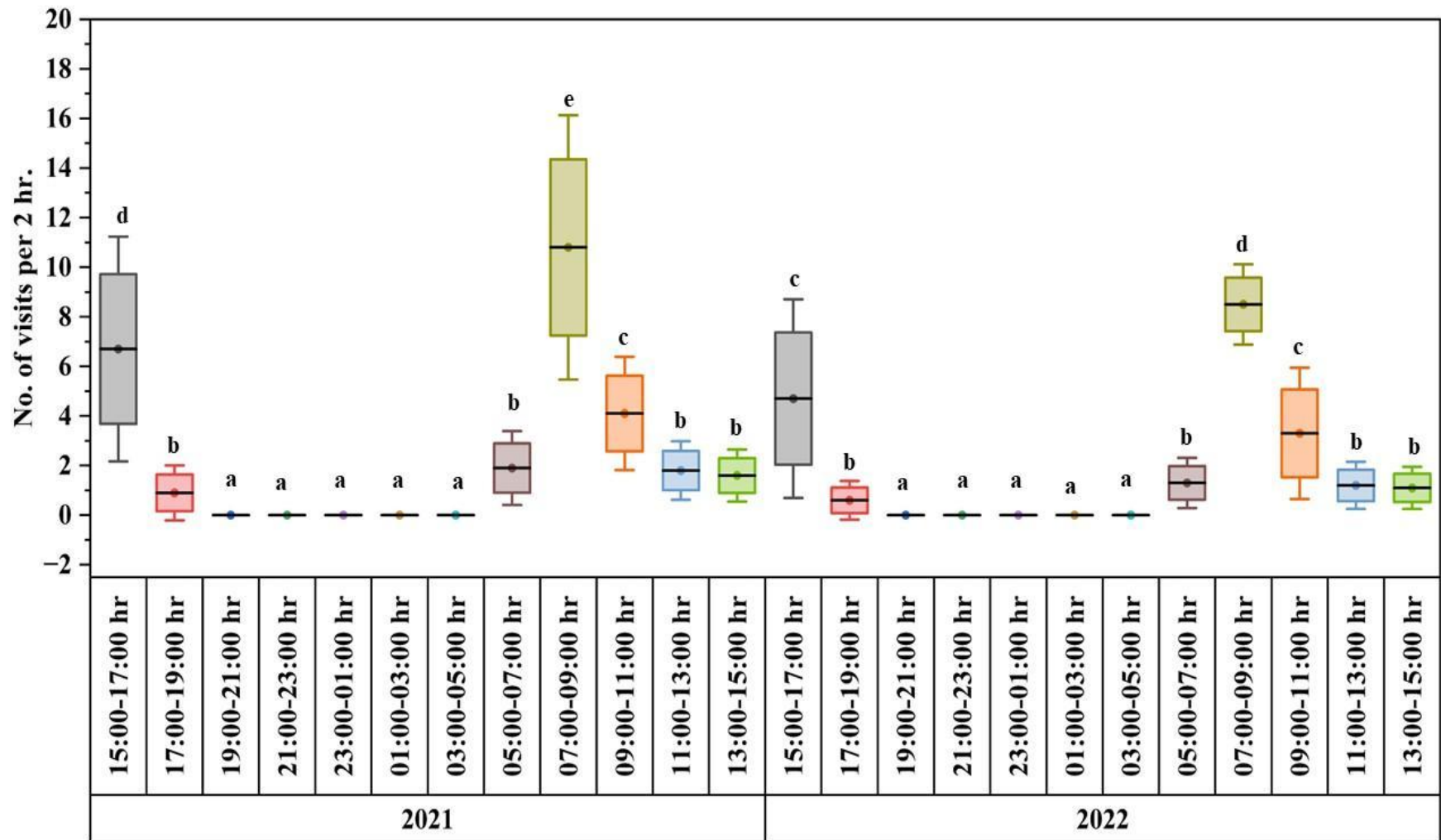


Figure 5.19. Visitation frequency of *Trigona* spp. w.r.t. to time block for the year 2021 and 2022.

5.4.5. Visitation frequency of *Trigona* spp.

The visitation patterns of *Trigona* spp. in 2021 and 2022 exhibit clear temporal trends, characterized by marked peaks of activity during the early morning and late afternoon hours. In 2021, the highest visitation frequency was recorded between 07:00 and 09:00 hours, with a mean of 10.80 visits per 2 hours, followed by a substantial decrease in activity after this period (Figure 5.19.). The visitation frequency between 15:00 and 17:00 hours was also notable, reaching 6.70 visits per 2 hours. Conversely, no visitation was recorded during the night and early morning hours (19:00 to 05:00 hours), suggesting a clear preference for diurnal foraging (Figure 5.19.). Additionally, periods such as 17:00 to 19:00 hours showed a significant reduction in visitation (0.90 visits per 2 hours). Standard deviations in 2021 ranged from 0.70 to 3.55, indicating some variability in visitation patterns, particularly during the peak activity periods. In 2022, similar patterns were observed, although the overall visitation frequency was lower compared to 2021. The highest visitation in 2022 occurred between 07:00 and 09:00 hours (8.50 visits per 2 hours), and the late afternoon period (15:00 to 17:00 hours) saw 4.70 visits per 2 hours (Figure 5.19.). As in 2021, no visitation was recorded during the night and early morning hours, reinforcing the species' preference for daylight activity. The visitation frequency during the 17:00 to 19:00 hours block was reduced further in 2022 (0.60 visits per 2 hours), and overall variability in visitation decreased, with standard deviations ranging from 0.57 to 1.77. This suggests that *Trigona* spp. exhibited more consistent foraging behavior in 2022, although activity levels were generally lower compared to the previous year. These findings underscore the species' strong preference for diurnal foraging and suggest that environmental factors or changes in resource availability may be influencing its temporal activity patterns.

5.4.6. Visitation frequency of *Vespa affinis*

The visitation patterns of *Vespa affinis* in 2021 and 2022 demonstrate clear temporal trends, with significant activity observed in the afternoon and early evening hours. In 2021, the highest mean visitation frequency occurred between 15:00 and 17:00 hours,

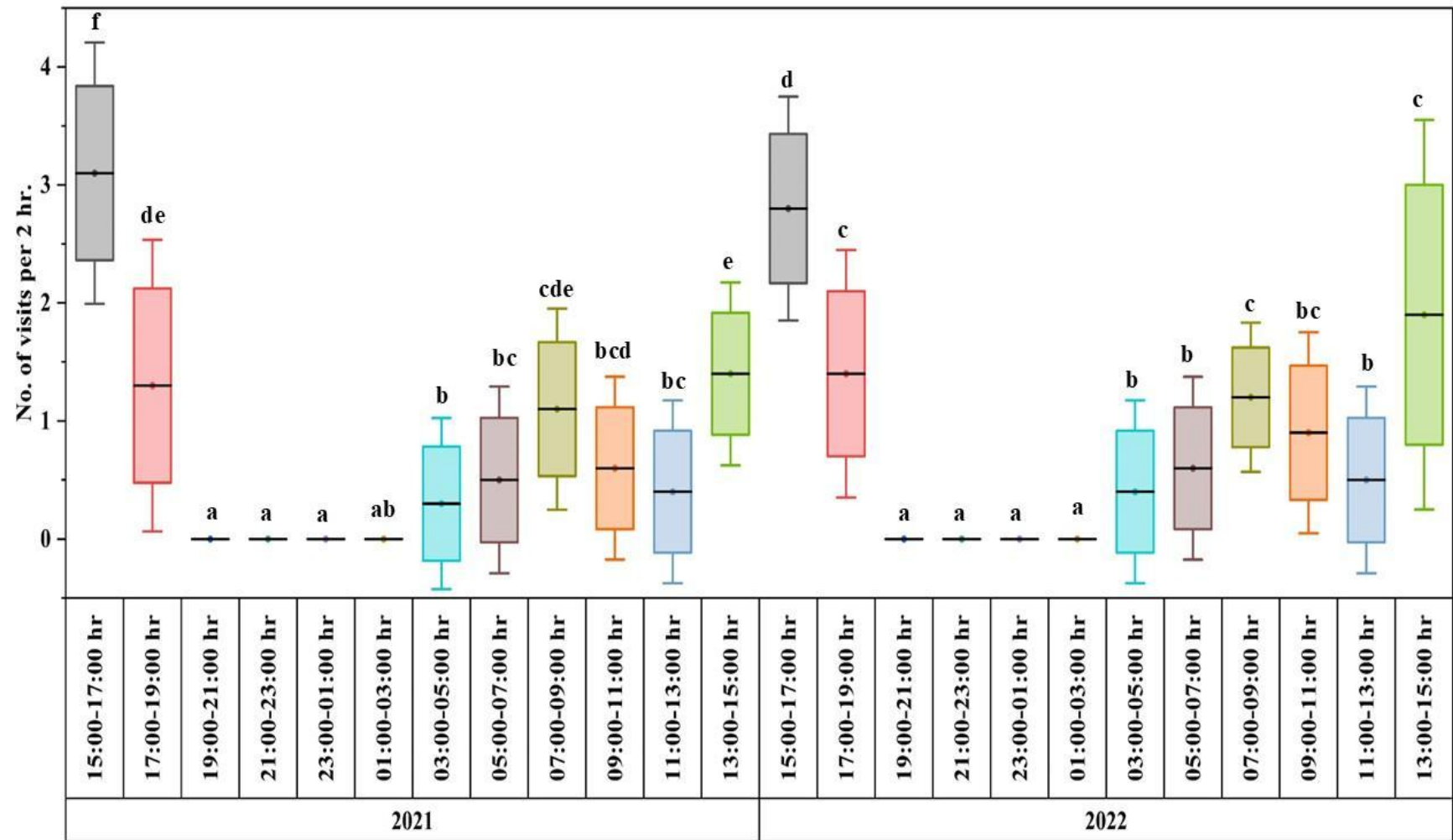


Figure 5.20. Visitation frequency of *Vespa affinis* w.r.t. to time block for the year 2021 and 2022.

with 3.10 visits per 2 hours, followed by a moderate decrease during the 13:00 to 15:00 hours (1.40 visits per 2 hours) (Figure 5.20.). Significantly, no visitation was observed during the night and early morning hours between 19:00 and 03:00, indicating a distinct period of inactivity. Lower visitation frequencies were recorded during the early morning with 0.30 visits per 2 hours between 03:00 and 05:00 hours, and 0.50 visits per 2 hrs. in (05:00 - 07:00) hrs (Figure 5.20.). The standard deviations across time blocks in 2021 ranged from 0.52 to 0.82, suggesting moderate variability in visitation, with the highest variation occurring during the late afternoon and early evening periods. In 2022, similar trends were observed, with the highest visitation frequency recorded between 15:00 and 17:00 hours (2.80 visits per 2 hours), although this was lower than the 2021 peak. The visitation frequency also declined in the 17:00 to 19:00 hours period (1.40 visits per 2 hours) and remained absent during the night and early morning hours (19:00 to 03:00 hours) (Figure 5.20.). Morning activity levels between 07:00 and 09:00 hours were recorded at 1.20 visits per 2 hours, and the lowest visitation occurred between 03:00 and 05:00 hours (0.40 visits per 2 hours) (Figure 5.20.). Standard deviations in 2022 ranged from 0.42 to 1.10, indicating increased variability in visitation rates compared to 2021, particularly in the afternoon hours. These findings underscore the species' preference for diurnal activity and highlight a consistent pattern of reduced activity during night time hours. The observed decrease in visitation frequency in 2022 relative to 2021 suggests potential changes in environmental or ecological factors influencing *V. affinis*'s foraging behavior, warranting further investigation to understand the underlying causes and their ecological implications.

5.4.7. Visitation frequency of *Phimenes flavopictus*

The visitation frequency of *Phimenes flavopictus* across 2021 and 2022 reveals distinct temporal patterns, with significant activity occurring in the late afternoon and early morning hours. In 2021, the highest visitation frequency was recorded during the 17:00–19:00 hour period, with a mean of 5.30 visits per 2 hours, followed by 15:00–17:00 hours, which saw 3.20 visits per 2 hours (Figure 5.21.). Activity was essentially absent during the late evening and early morning hours, with no visitation recorded

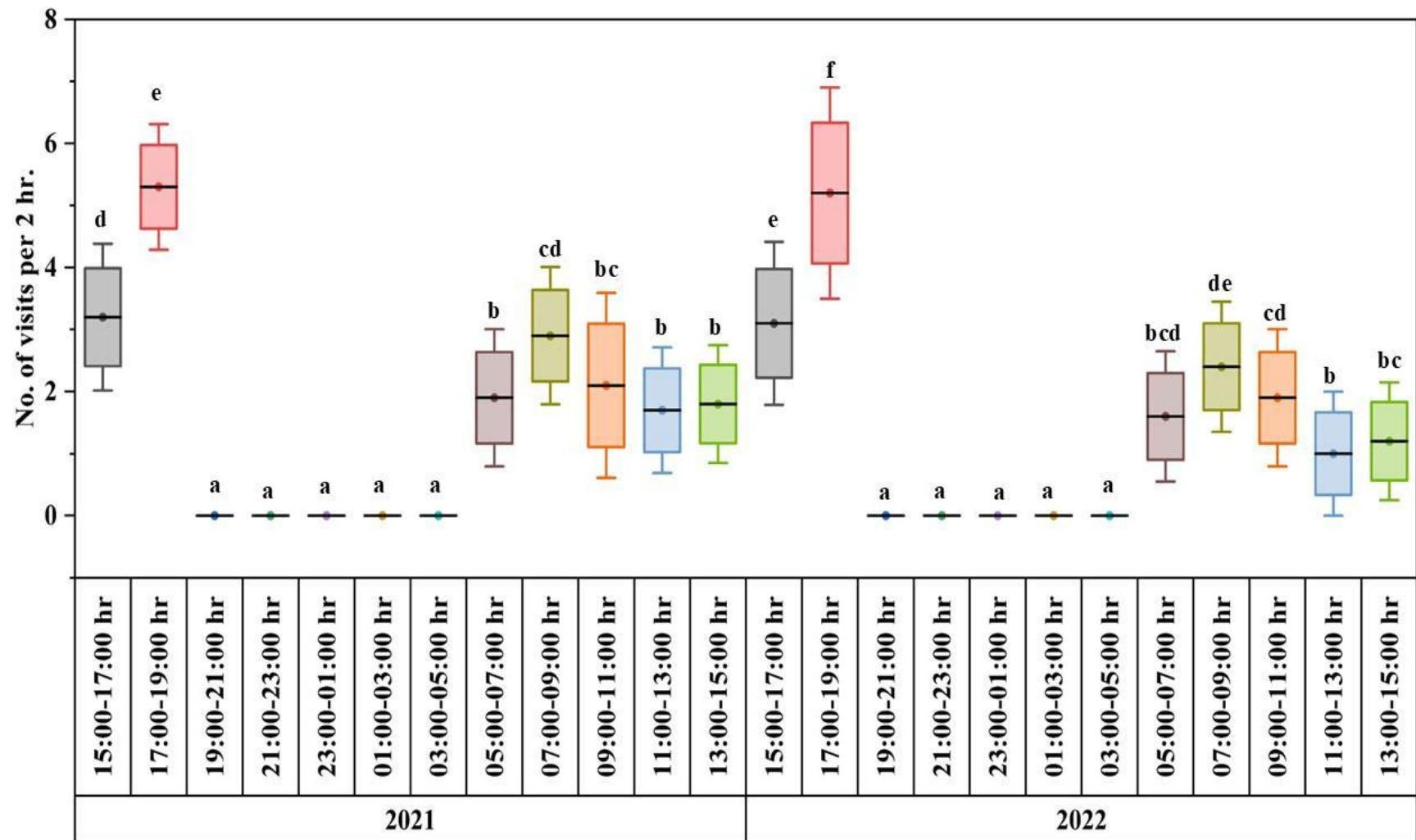


Figure 5.21. Visitation frequency of *Phimenes flavopictus* w.r.t. to time block for the year 2021 and 2022.

between 19:00 and 05:00 hrs. The morning period between (05:00-07:00) hrs exhibited moderate visitation (1.90 visits per 2 hours), with a 2.90 visits per 2 hours between 07:00 and 09:00 hours. The visitation frequency during the remaining time blocks, such as 09:00-11:00 hours (2.10 visits per 2 hours) and 11:00-13:00 hours (1.70 visits per 2 hours), followed a decreasing trend throughout the day (Figure 5.21.). The standard deviations in 2021, ranging from 0.63 to 0.99, suggest some variability in visitation patterns, particularly during late morning and evening periods, where activity fluctuated. In 2022, visitation frequencies were generally lower compared to the previous year, with the highest visitation still occurring between 17:00 and 19:00 hours (5.20 visits per 2 hours) (Figure 5.21.). Visitation during the 15:00-17:00 hours period also showed some decline to 3.10 visits per 2 hours, similar to 2021, but the early morning activity was lower at 1.60 visits per 2 hours (05:00-07:00 hours) (Figure 5.21.). The species continued to exhibit no activity during the late night to early morning hours, consistent with the pattern observed in 2021. The overall visitation frequency showed a downward trend across 2022, particularly from 09:00 to 13:00 hours, where frequencies dropped further, with 1.90 visits per 2 hours during 09:00–11:00 hours and 1.00 visits per 2 hours during 11:00-13:00 hours (Figure 5.21.). Standard deviations in 2022 ranged from 0.63 to 1.14, showing slight increases in variability compared to 2021. These findings emphasize a consistent foraging pattern in *P. flavopictus*, with heightened activity in the late afternoon and early morning hours, and a marked decrease in activity during the late-night and early-morning periods. The observed decline in visitation frequency between the two years could be indicative of environmental factors influencing foraging behavior, necessitating further investigation into the ecological drivers of these patterns.

5.4.8. Visitation frequency of *Achaea serva*

The visitation patterns of *Achaea serva* in 2021 and 2022 exhibit limited activity, primarily concentrated during the evening and night hours, with very little to no foraging observed during the day. In 2021, the highest visitation frequency was recorded between 19:00 and 21:00 hours, with an average of 2.50 visits per 2 hours, followed by a reduction in visitation during the 21:00 to 23:00 hours (1.60 visits per 2

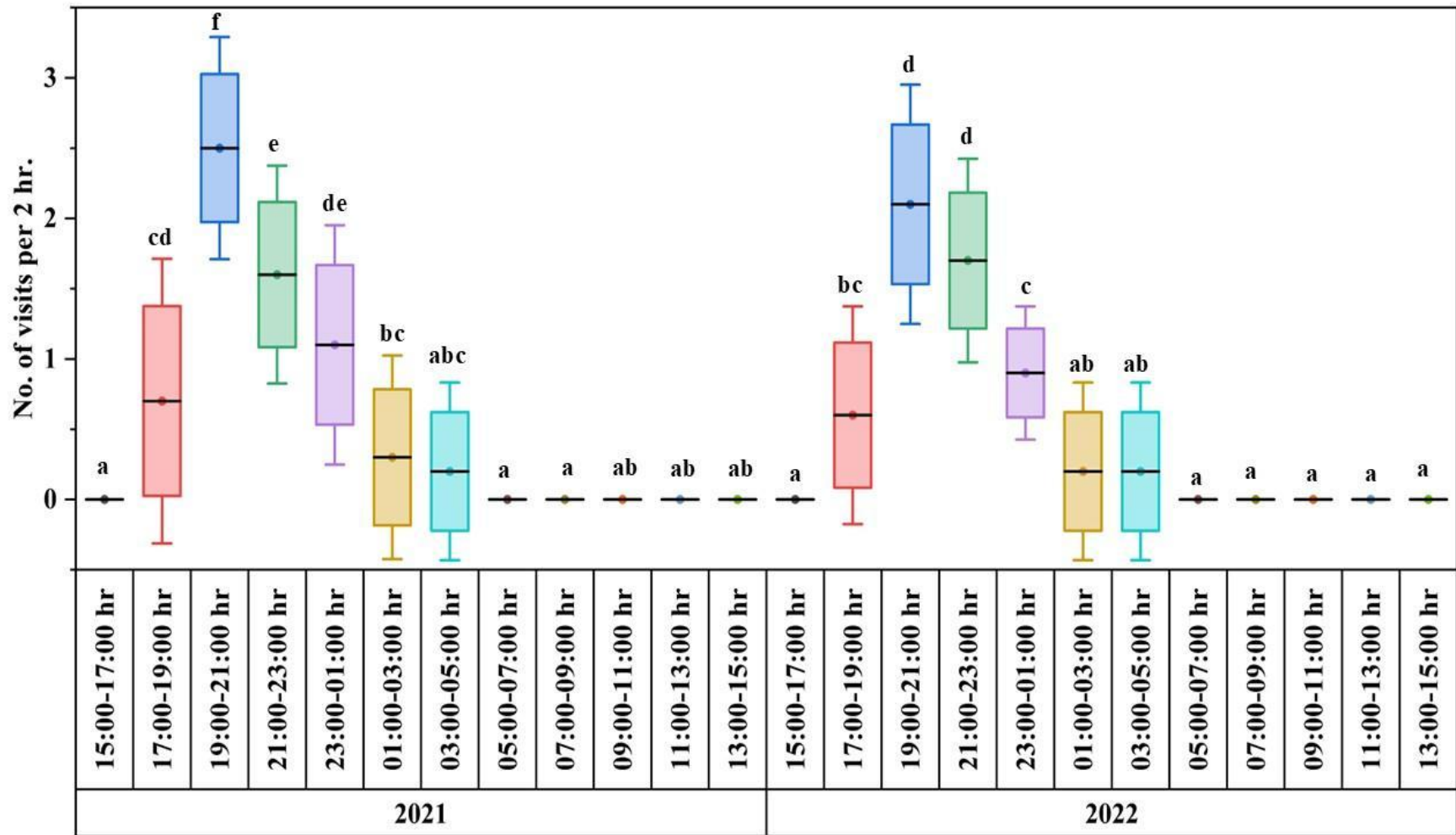


Figure 5.22. Visitation frequency of *Achaea serva* w.r.t. to time block for the year 2021 and 2022.

hours) and 23:00 to 01:00 hours (1.10 visits per 2 hours) (Figure 5.22.). During the early morning hours (01:00–03:00) hrs and (03:00–05:00) hrs, the visitation frequency was minimal, at 0.30 and 0.20 visits per 2 hours, respectively. Additionally, there was no recorded visitation between 05:00 and 17:00 hours. The standard deviations in 2021, ranging from 0.42 to 0.67, indicate some variability in visitation frequency, particularly during the evening and night periods, though overall activity was low. In 2022, the visitation frequency remained relatively consistent, with the highest frequency observed between 19:00 and 21:00 hours (2.10 visits per 2 hours), followed by a slight decrease in the 21:00 to 23:00 hours period (1.70 visits per 2 hours) (Figure 5.22.). Similar to 2021, there was no activity between 05:00 and 17:00 hours. Early morning activity was also low, with 0.20 visits per 2 hours recorded between 01:00 and 03:00 hours and 03:00 to 05:00 hours (Figure 5.22.). The standard deviations in 2022 ranged from 0.32 to 0.57, suggesting less variability compared to 2021. These findings suggest that *A. serva* exhibits nocturnal foraging behavior, with activity peaking during the evening and night hours, and inactivity during daylight hours. The slight decrease in activity observed in 2022 may reflect subtle changes in environmental or ecological factors, indicating a need for further research to investigate potential drivers of this variation.

5.4.9. Visitation frequency of *Agrotis infusa*

The visitation patterns of *Agrotis infusa* across the years 2021 and 2022 reveal a distinct nocturnal activity rhythm, with the highest visitation frequencies recorded during the late evening and night hours. In 2021, visitation peaked between 21:00 and 23:00 hours, with a mean of 1.60 visits per 2 hours, followed by 1.10 visits per 2 hrs in (23:00-01:00) hrs (Figure 5.23.). The frequency further decreased to 0.40 visits per 2 hours between 01:00 and 03:00 hours, and minimal activity was recorded in the early morning hours, with 0.20 visits per 2 hours between 03:00 and 05:00 hours. No activity was observed during the daytime hours (05:00–17:00) periods (Figure 5.23.). Standard deviations for 2021 ranged from 0.42 to 0.70, indicating moderate variability in visitation, with a higher degree of fluctuation during the night-time periods. In 2022, *A. infusa* followed a similar pattern of visitation, with a peak recorded during 21:00-

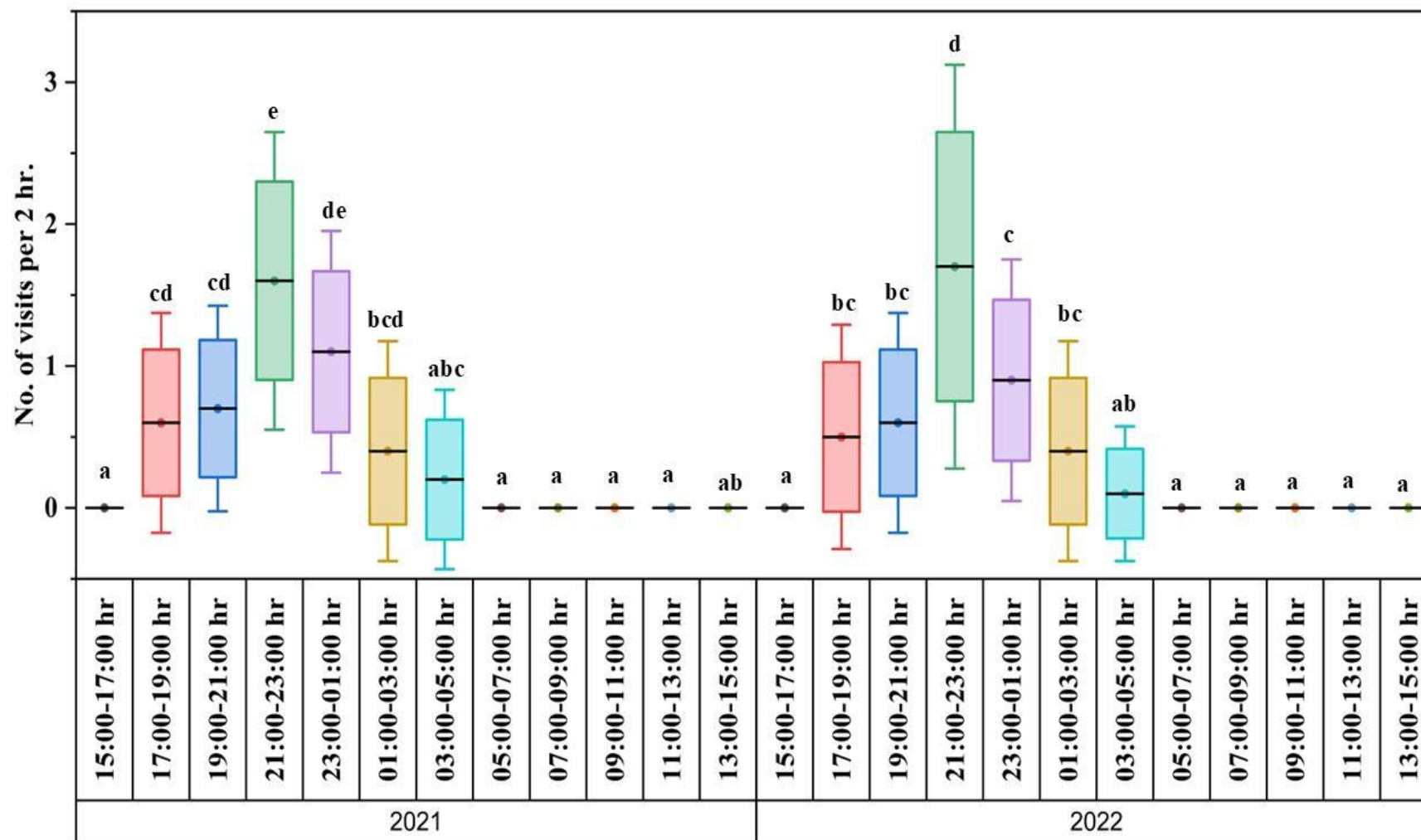


Figure 5.23. Visitation frequency of *Agrotis infusa* w.r.t. to time block for the year 2021 and 2022.

23:00 hours (1.70 visits per 2 hours) and moderate visitation at 23:00–01:00 hours (0.90 visits per 2 hours). The frequency of visitation during 19:00–21:00 hours was 0.60 visits per 2 hours, lesser than the previous year (Figure 5.23.). The early morning period (03:00–05:00 hours) showed a further decline in activity, with a frequency of only 0.10 visits per 2 hours. As with 2021, no activity was recorded during the daylight hours (05:00–17:00 hours) (Figure 5.23.). The standard deviations in 2022 ranged from 0.32 to 0.95, indicating some variability in visitation, particularly during the late-night hours. These results suggest that *A. infusa* exhibits a clear preference for nocturnal and crepuscular foraging, with little to no activity during the day. The slight decrease in visitation frequency observed in 2022 compared to 2021 could be indicative of changes in environmental or ecological conditions, warranting further investigation to explore the factors influencing these temporal variations.

5.4.10. Visitation frequency of *Ercheia cyllaria*

The visitation patterns of *Ercheia cyllaria* in 2021 and 2022 demonstrate a clear nocturnal foraging behavior, with the highest visitation frequencies recorded during the evening and night hours. In 2021, the peak visitation occurred between 21:00 and 23:00 hours, with a mean of 1.50 visits per 2 hours, followed by a slight decline in the night hours, where 0.70 visits per 2 hours were recorded in (19:00–21:00) hrs (Figure 5.24.). Activity further decreased, with 0.60 visits per 2 hrs in (23:00–01:00) hrs, and the least visitation of 0.10 visits per 2 hours in (03:00–05:00) hrs (Figure 5.24.). Notably, no visitation was observed during the daytime periods (05:00 to 17:00 hours), suggesting that *E. cyllaria* is primarily active at night. The standard deviations in 2021 ranged from 0.32 to 0.85, indicating moderate variability in visitation frequency, especially during the late evening and night. In 2022, visitation frequencies followed a similar pattern, with a slight increase in activity compared to 2021. The highest frequency in 2022 was recorded between 21:00 and 23:00 hours (1.70 visits per 2 hours), followed by 0.90 visits per 2 hrs in (19:00–21:00) hrs (Figure 5.24.). Activity levels in the night period (23:00–01:00 hours) were more than 2021, with 0.70 visits per 2 hours. As in 2021, minimal activity was recorded during the early morning periods, and no visitation was recorded during the daytime hours (05:00 to 17:00) hrs

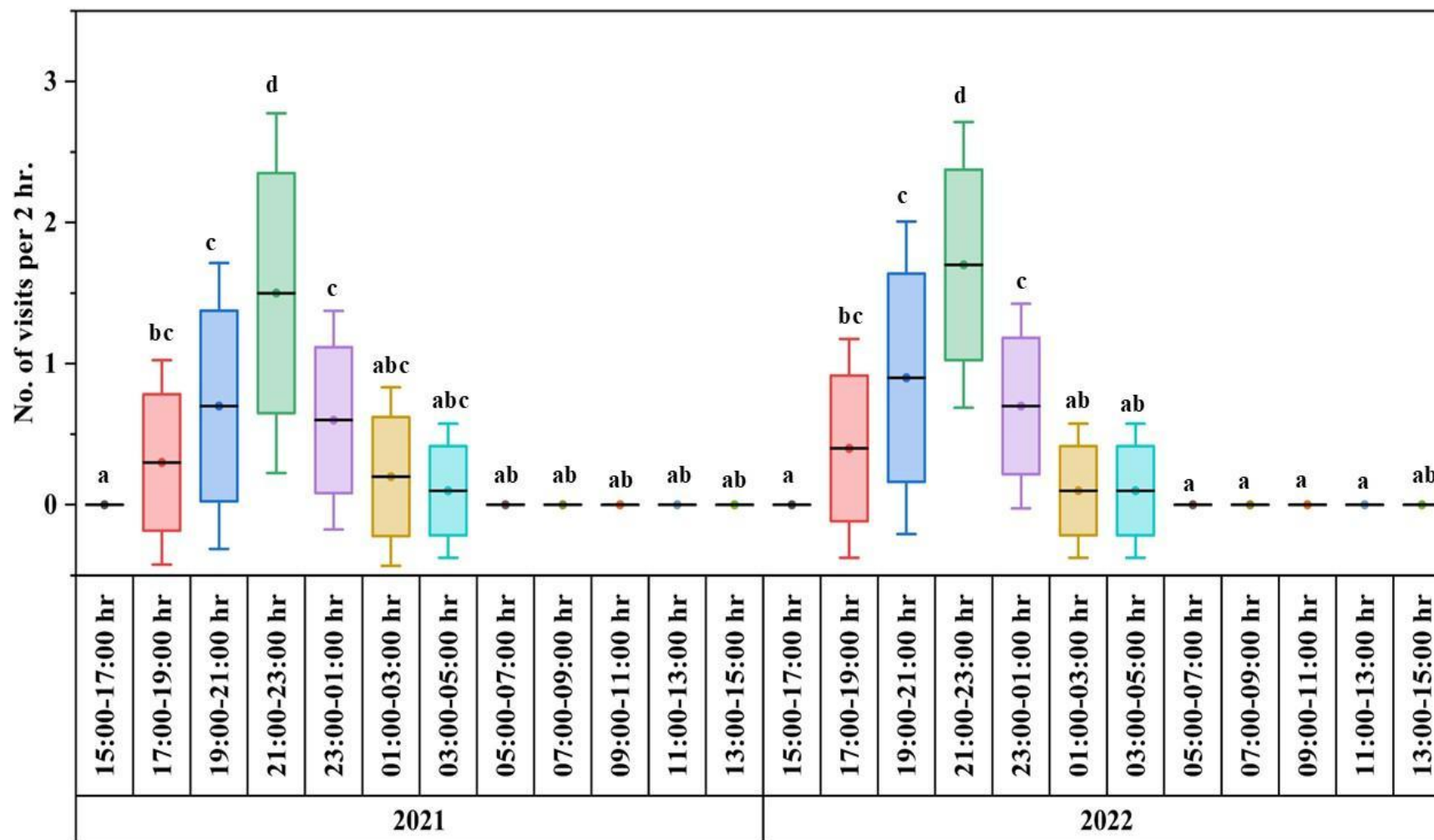


Figure 5.24. Visitation frequency of *Ercheia cyllaria* w.r.t. to time block for the year 2021 and 2022.

(Figure 5.24.). The standard deviations in 2022 ranged from 0.32 to 0.74, reflecting slight variability in visitation. These patterns indicate that *E. cyllaria* exhibits strong nocturnal and crepuscular activity, with little to no foraging during daylight hours. The slight increase in visitation observed in 2022 compared to 2021 may be reflective of subtle changes in environmental conditions or resource availability, warranting further investigation to explore the ecological factors influencing these shifts.

5.4.11. Visitation frequency of *Eudocima phalonia*

The visitation frequency of *Eudocima phalonia* in both 2021 and 2022 demonstrates a distinct nocturnal activity pattern, with a clear peak in visitation during the evening and early night hours. In 2021, the highest visitation frequency was recorded between 19:00 and 21:00 hours, with an average of 1.60 visits per 2 hours, followed by a slight decline in frequency during the 21:00 to 23:00 hours (1.20 visits per 2 hours) (Figure 5.25.). Visitation continued to decrease through the night, with 0.70 visits per 2 hours between 23:00 and 01:00 hours and 0.40 visits per 2 hours between 01:00 and 03:00 hours. Minimal activity was observed between 03:00 and 05:00 hours (0.10 visits per 2 hours), and no visits were recorded during the daytime, between 05:00 and 15:00 hrs (Figure 5.25.). The standard deviations in 2021 ranged from 0.32 to 0.70, suggesting moderate variability in visitation, particularly during the evening and night periods. A similar visitation pattern was observed in 2022, although with slightly reduced frequencies. The highest visitation in 2022 occurred again between 19:00 and 21:00 hours (1.50 visits per 2 hours), followed by 1.40 visits per 2 hours between 21:00 and 23:00 hrs. Visitation during late night and early morning periods continued to show low levels, with 0.30 visits per 2 hrs in (01:00-03:00) hrs (Figure 5.25.). The standard deviations in 2022 ranged from 0.32 to 0.70, reflecting some variability in visitation rates, particularly during the later hours. Notably, there were no recorded visits during the early morning or daytime hours, further reinforcing the species' preference for nocturnal activity. The decrease in visitation frequency in 2022 relative to 2021 suggests potential shifts in environmental or ecological factors influencing foraging behavior, which warrants further research into the specific drivers of these changes.

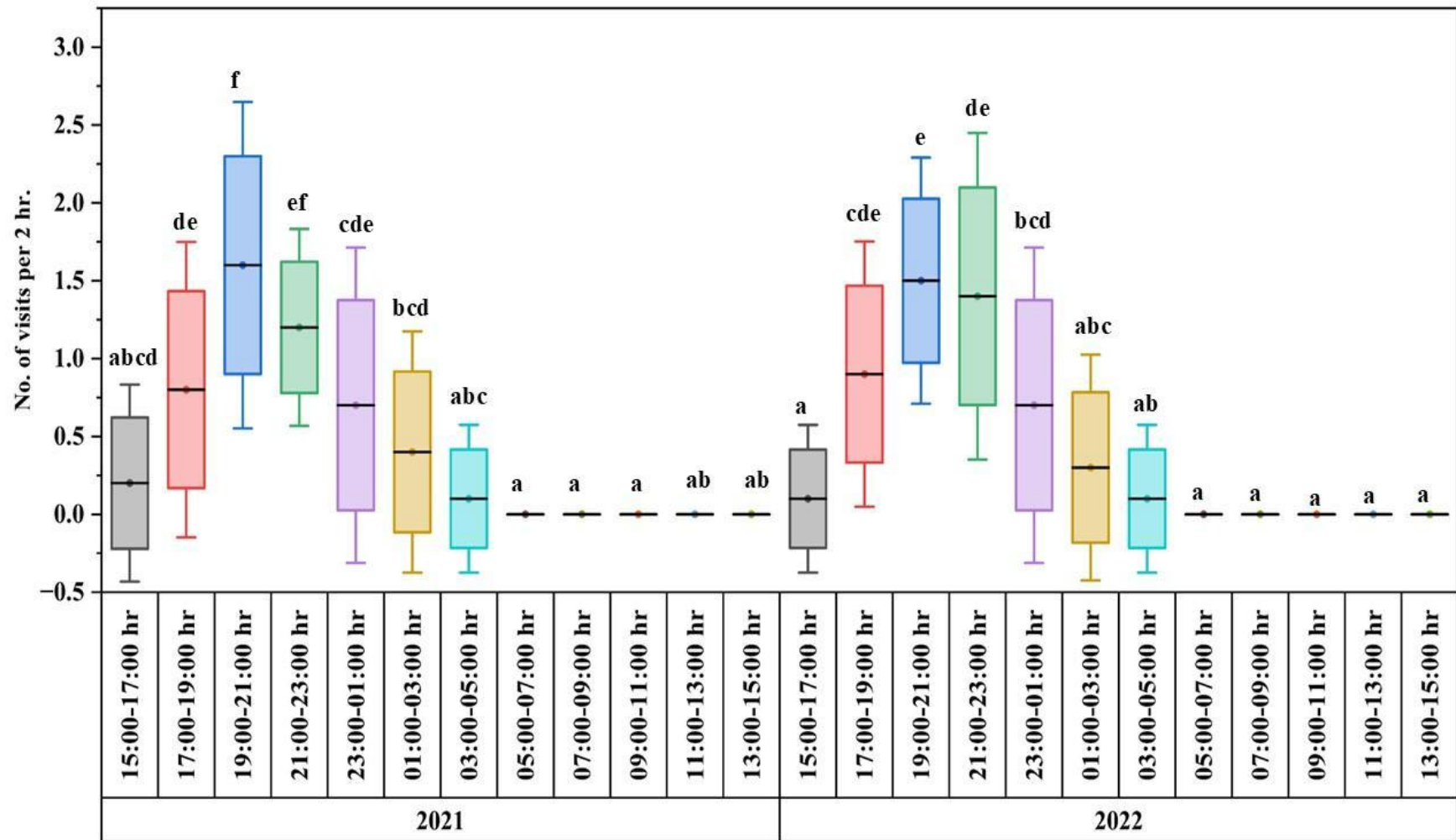


Figure 5.25. Visitation frequency of *Eudocima phalonia* w.r.t. to time block for the year 2021 and 2022

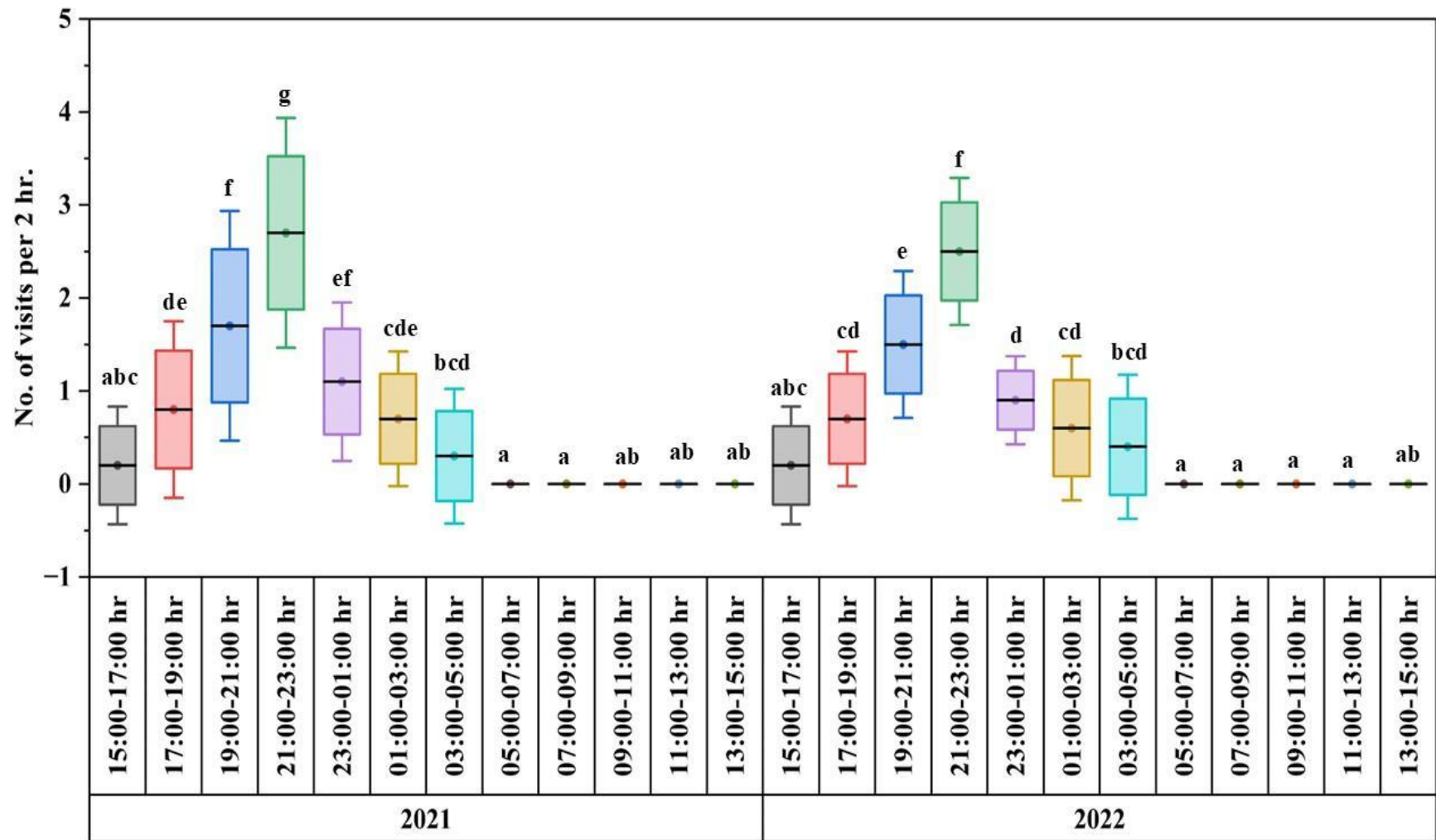


Figure 5.26. Visitation frequency of *Hulodes caranea* w.r.t. to time block for the year 2021 and 2022.

5.4.12. Visitation frequency of *Hulodes caranea*

The visitation frequency of *Hulodes caranea* in 2021 and 2022 exhibited a consistent nocturnal activity pattern, with significant peaks in visitation during the late evening and early night hours. In 2021, the highest visitation frequency was recorded between 21:00 and 23:00 hours, with a mean of 2.70 visits per 2 hours, followed by a slightly lower frequency between 19:00 and 21:00 hours (1.70 visits per 2 hours) (Figure 5.26.). The visitation rate remained moderate between 23:00 and 01:00 hours (1.10 visits per 2 hours) and decreased further to 0.70 visits per 2 hours between 01:00 and 03:00 hours. Visitation was minimal during the early morning, with 0.30 visits per 2 hours recorded in (03:00-05:00) hrs (Figure 5.26.). There was no recorded visitation during the daytime period (05:00–15:00 hours) confirming the species' preference for nocturnal activity. In 2022, similar patterns were observed, although the overall visitation frequency was slightly lower than in 2021. The highest mean visitation frequency in 2022 was recorded between 21:00 and 23:00 hours (2.50 visits per 2 hours), followed by 1.50 visits per 2 hrs in (19:00-21:00) hrs. Visitation continued to decline during the night, with 0.90 visits per 2 hrs in (23:00-01:00) hrs and 0.60 visits per 2 hrs in (01:00-03:00) hrs (Figure 5.26.). As in 2021, no visitation was recorded during the daytime period from 05:00 to 15:00 hours. Standard deviations in both years ranged from 0.32 to 0.82, indicating moderate variability in visitation, especially during the evening and night periods. The slight decrease in visitation frequency in 2022 relative to 2021 may suggest subtle changes in environmental or ecological factors influencing the foraging behavior of *H. caranea*, warranting further investigation into the underlying causes of this temporal variation.

5.4.13. Visitation frequency of *Psyrassa unicolor*

The visitation patterns of *Psyrassa unicolor* in 2021 and 2022 display a strong preference for nocturnal activity, with peak visitation frequencies observed during the evening and early night hours. In 2021, the highest visitation frequency occurred between 21:00 and 23:00 hours, with an average of 6.20 visits per 2 hours, followed by 4.80 visits per 2 hours during the 19:00 to 21:00 hours period (Figure 5.27.). The

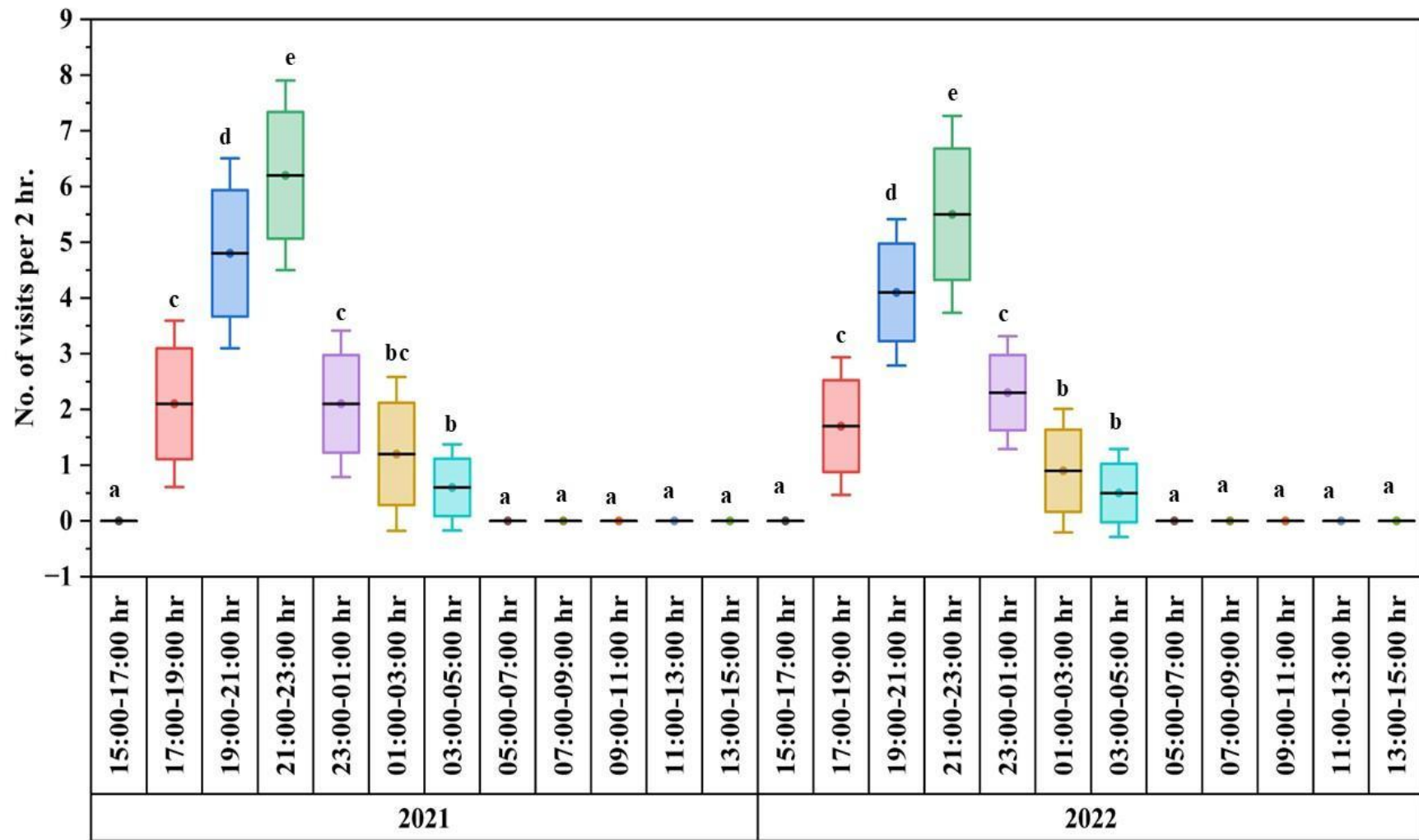


Figure 5.27. Visitation frequency of *Psyrassa unicolor* w.r.t. to time block for the year 2021 and 2022.

visitation rate dropped to 2.10 visits per 2 hours between 23:00 and 01:00 hours and further declined to 1.20 visits per 2 hours between 01:00 and 03:00 hours. Visitation was minimal during the early morning, with only 0.60 visits per 2 hours recorded between 03:00 and 05:00 hours, and no visitation was recorded during the daytime period (05:00–17:00 hours) (Figure 5.27.). The standard deviations for 2021, which ranged from 0.52 to 1.14, suggest some degree of variability in visitation frequency, particularly during the evening and early night periods. In 2022, visitation frequencies were slightly lower than in 2021, with the highest frequency recorded between 21:00 and 23:00 hours (5.50 visits per 2 hours) and 4.10 visits per 2 hrs in (19:00–21:00) hrs. Visitation continued to decrease during the late night, with 2.30 visits per 2 hours between 23:00 and 01:00 hours and 0.90 visits per 2 hours between 01:00 and 03:00 hours. The early morning period saw further reductions, with only 0.50 visits per 2 hours recorded between 03:00 and 05:00 hours. As in 2021, no visitation occurred during the day time hours (05:00–17:00 hours) (Figure 5.27.). The standard deviations in 2022 ranged from 0.53 to 1.18, indicating moderate variability in visitation, particularly in the evening and night periods. The observed decrease in visitation frequency in 2022 compared to 2021 could reflect ecological or environmental changes affecting *P. unicolor*, suggesting that further research into these potential drivers is needed to better understand the factors influencing temporal shifts in visitation patterns.

5.4.14. Visitation frequency of *Ariadne merione*

The visitation patterns of *Ariadne merione* in 2021 and 2022 reveal a clear preference for activity during the daylight hours, with peak visitation occurring in the late morning and early afternoon. In 2021, the highest visitation frequency was observed between 09:00 and 11:00 hours, with 0.70 visits per 2 hours, followed by moderate activity during 11:00–13:00 hours (0.60 visits per 2 hours) and 07:00–09:00 hours (0.50 visits per 2 hours). Visitation was notably lower during the early morning hours, with 0.10 visits per 2 hours recorded between 05:00 and 07:00 hours and 0.20 visits per 2 hours during 13:00–15:00, and 15:00–17:00 hours (Figure 5.28.). No activity was recorded during the night or early morning periods, from 17:00–05:00 hours, which suggests

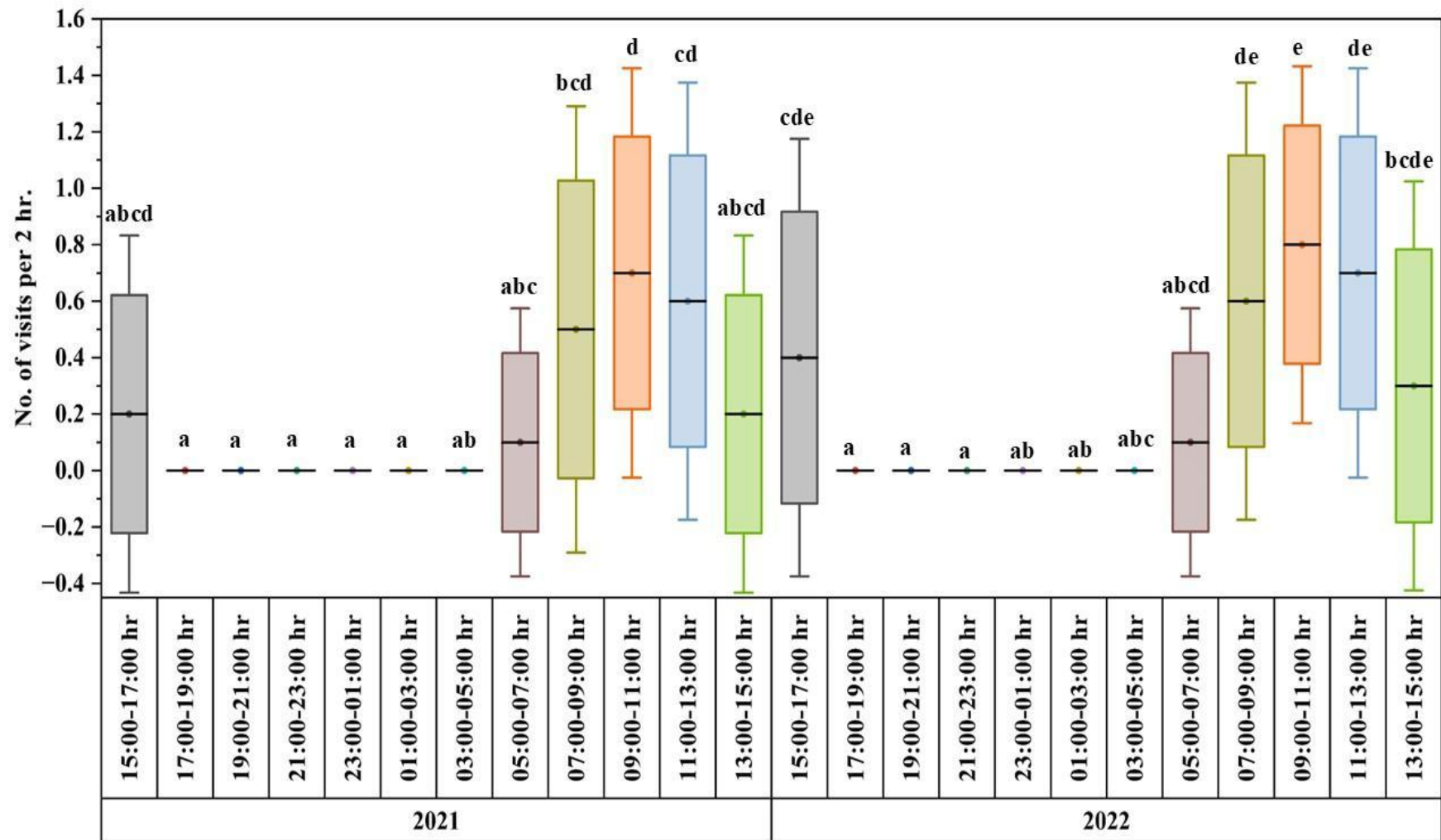


Figure 5.28. Visitation frequency of *Ariadne merione* w.r.t. to time block for the year 2021 and 2022.

that the species exhibits diurnal foraging behavior. The standard deviations in 2021 ranged from 0.32 to 0.53, indicating some variability in visitation rates across the day, particularly in the late morning and early afternoon periods. In 2022, similar trends were observed, although the visitation frequency between 09:00 and 11:00 hours increased slightly to 0.80 visits per hour, while activity remained moderate during 11:00–13:00 hours (0.70 visits per 2 hours) and 07:00–09:00 hours (0.60 visits per 2 hours) (Figure 5.28.). The early morning and late afternoon periods continued to show the lowest visitation rates, with 0.10 visits per hour recorded between 05:00 and 07:00 hours and 0.30 visits per 2 hours during 13:00–15:00 hours (Figure 5.28.). As in 2021, no activity was observed during the night and early morning hours. The standard deviations for 2022 ranged from 0.32 to 0.52, reflecting moderate variability in visitation, similar to 2021. These results suggest that *A. merione* exhibits consistent diurnal activity, with a clear preference for foraging during the morning and early afternoon. The slight increase in visitation frequency in 2022 compared to 2021 may reflect subtle changes in environmental conditions or resource availability, warranting further investigation into the ecological factors that may influence these temporal shifts in foraging behavior.

5.4.15. Visitation frequency of bats

The visitation patterns of bat across the years 2021 and 2022 demonstrate a distinct nocturnal foraging behavior, with peak activity occurring during the evening and early night hours. In 2021, the highest visitation frequency was recorded between 21:00 and 23:00 hours, with a mean of 40.70 visits per 2 hours, followed by a significant decrease in activity after midnight (Figure 5.29.). The frequency dropped to 23.70 visits per 2 hours between 23:00 and 01:00 hours and further declined to 14.90 visits per 2 hrs in (01:00-03:00) hrs (Figure 5.29.). Activity remained relatively low between 03:00 and 05:00 hours, with 8.10 visits per 2 hours recorded (Figure 5.29.). No visitation was recorded during the daytime periods, particularly between 05:00 and 17:00 hours. In contrast, the visitation frequency in 2022 showed a slight reduction across the board compared to the previous year. However, the same nocturnal pattern persisted, with the highest frequency occurring between 21:00 and 23:00 hours (38.50 visits per 2

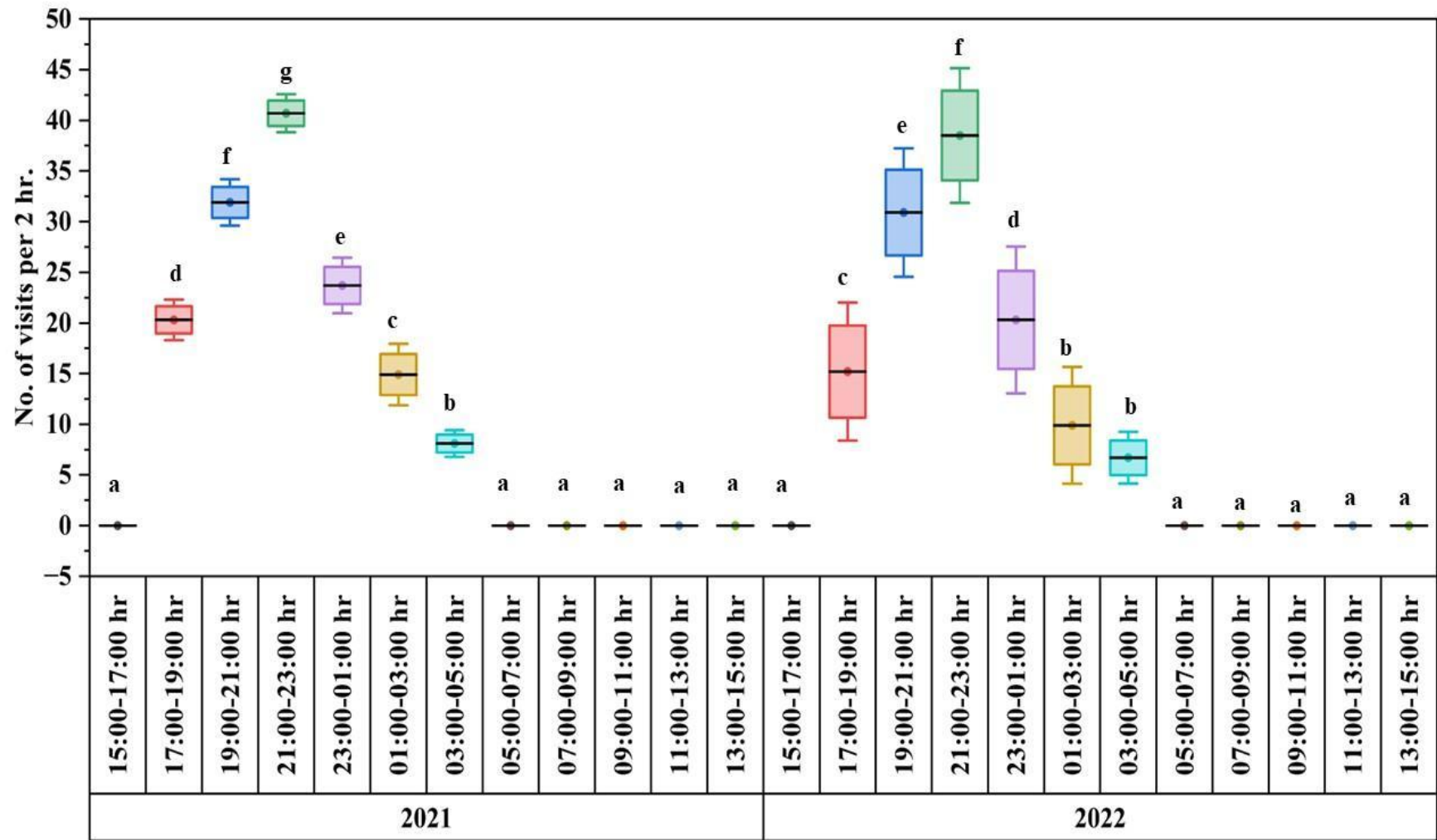


Figure 5.29. Visitation frequency of bat w.r.t. to time block for the year 2021 and 2022.

2 hours). Activity levels remained moderate between 19:00 and 21:00 hours (30.90 visits per 2 hours) and between 23:00 and 01:00 hours (20.30 visits per 2 hours), with a decrease in visitation recorded during the early morning hrs of 03:00 to 05:00 hours (6.70 visits per 2 hours) (Figure 5.29.). In both years, no visits were observed during the daytime periods from 05:00 to 17:00 hours. The standard deviations for 2021 and 2022 ranged from 0.88 to 4.83, reflecting moderate to high variability in visitation during the peak hours of activity, particularly in the evening and night. The reduction in visitation in 2022 suggests potential ecological or environmental factors that may be influencing the species' foraging behavior.

5.4.16. Visitation frequency of each pollinator for the year 2021 and 2022.

The visitation frequencies of pollinator species in 2021 and 2022 demonstrate notable shifts in activity levels, with some species consistently exhibiting higher visitation rates while others remained relatively inactive. In 2021, *A. cerana indica* recorded the highest visitation frequency of 17.63 visits per 2 hours, followed by bat with 11.63 visits per 2 hours, and *T. sessile* with 8.29 visits per 2 hours, indicating strong foraging activity for these species (Figure 5.30.). Other species, such as *Camponotus* spp. (3.25 visits per 2 hours) and *Trigona* spp. (2.32 visits per 2 hours), displayed moderate levels of visitation, while species like *V. affinis* (0.73 visits per 2 hours), *A. serva* (0.53 visits per 2 hours), and *E. cyllaria* (0.28 visits per 2 hours) exhibited relatively low activity (Figure 5.30.). Among the least active species were *A. merione* and *P. unicolor*, with visitation frequencies of 0.19 and 1.42 visits per 2 hours, respectively. In 2022, visitation frequencies showed slight reductions across several species (Figure 5.30.). *A. cerana indica* continued to be the dominant species in terms of visitation, though its frequency decreased to 15.40 visits per 2 hours. Similarly, bat showed a decline to 10.13 visits per 2 hours, and *T. sessile* reduced its frequency to 5.63 visits per 2 hours, although it remained relatively active. Other species such as *Camponotus* spp. (2.76 visits per 2 hours) and *B. bicoloratus* (1.20 visits per 2 hours) also exhibited reduced visitation, while species like *V. affinis* (0.81 visits per 2 hours), *P. flavopictus* (1.37 visits per 2 hours), and *P. unicolor* (1.25 visits per 2 hours) maintained relatively stable activity levels (Figure 5.30.). Species with consistently low visitation, such as *A. serva*

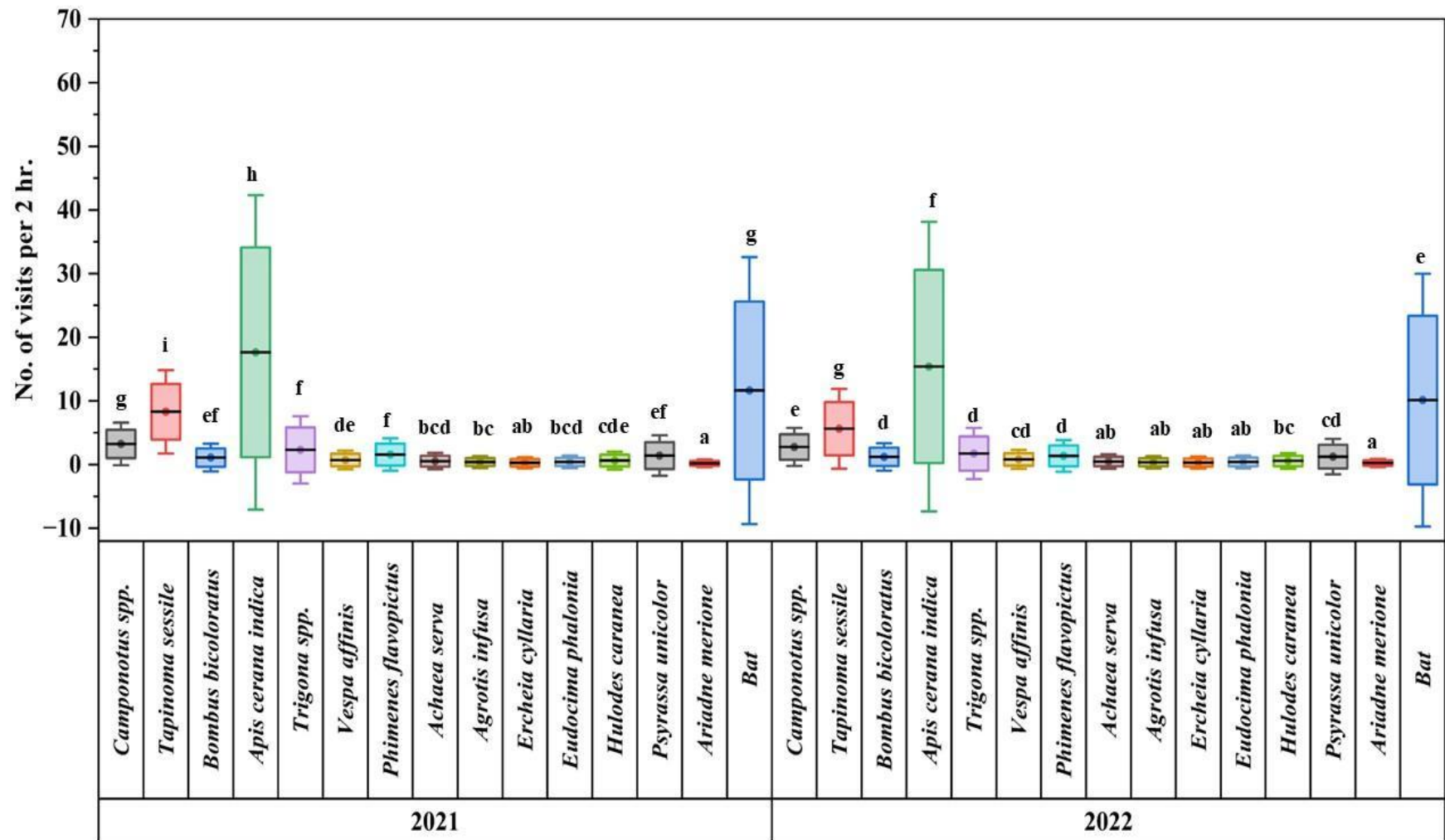


Figure 5.30. Visitation frequency of each pollinator for the year 2021 and 2022.

and *A. merione*, continued to show minimal activity in both years. These findings suggest that certain pollinators, particularly *A. cerana indica*, bat, and *T. sessile*, remain significant contributors to pollination throughout the study period, while others exhibit limited activity. The observed decreases in visitation in some species may reflect subtle changes in ecological or environmental conditions, highlighting the need for further research to identify the underlying factors that drive these temporal shifts in foraging behavior.

5.4.17. Visitation frequency of each pollinator for the year 2021 and 2022 as per family wise.

The visitation frequencies of various pollinator families in 2021 and 2022 exhibit marked differences in foraging activity, with some families showing sustained high visitation levels, while others demonstrated minimal contributions to pollination. In 2021, the Apidae family, which includes key pollinators such as *A. cerana indica*, recorded the highest visitation frequency at 21.05 visits per 2 hours, followed by Pteropodidae with 11.63 visits per 2 hours, and Formicidae with 11.54 visits per 2 hours (Figure 5.31.). These families dominated the visitation landscape, playing a significant role in the pollination process. The Vespidae family, representing wasps, exhibited moderate visitation with 2.30 visits per 2 hours, while the Erebididae family, which includes moth species, recorded 1.86 visits per 2 hours (Figure 5.31.). Other families, such as Cerambycidae (1.42 visits per 2 hours), Noctuidae (0.38 visits per 2 hours), and Nymphalidae (0.19 visits per 2 hours), showed low visitation frequencies, indicating their limited involvement in pollination during this period. In 2022, a slight decline in visitation was observed across most families. The Apidae family remained the most active but experienced a decrease to 18.33 visits per 2 hours, while Pteropodidae to 10.13 visits per 2 hours, and Formicidae decreased to 8.38 visits per 2 hours (Figure 5.31.). The Vespidae family showed a modest reduction in visitation frequency, dropping to 2.18 visits per 2 hours. Similarly, Erebididae recorded a slight decline to 1.78 visits per 2 hours. Families such as Cerambycidae (1.25 visits per 2 hours), Noctuidae (0.35 visits per 2 hours), and Nymphalidae (0.24 visits per 2 hours) also exhibited minor decreases in visitation compared to 2021 (Figure 5.31.). These

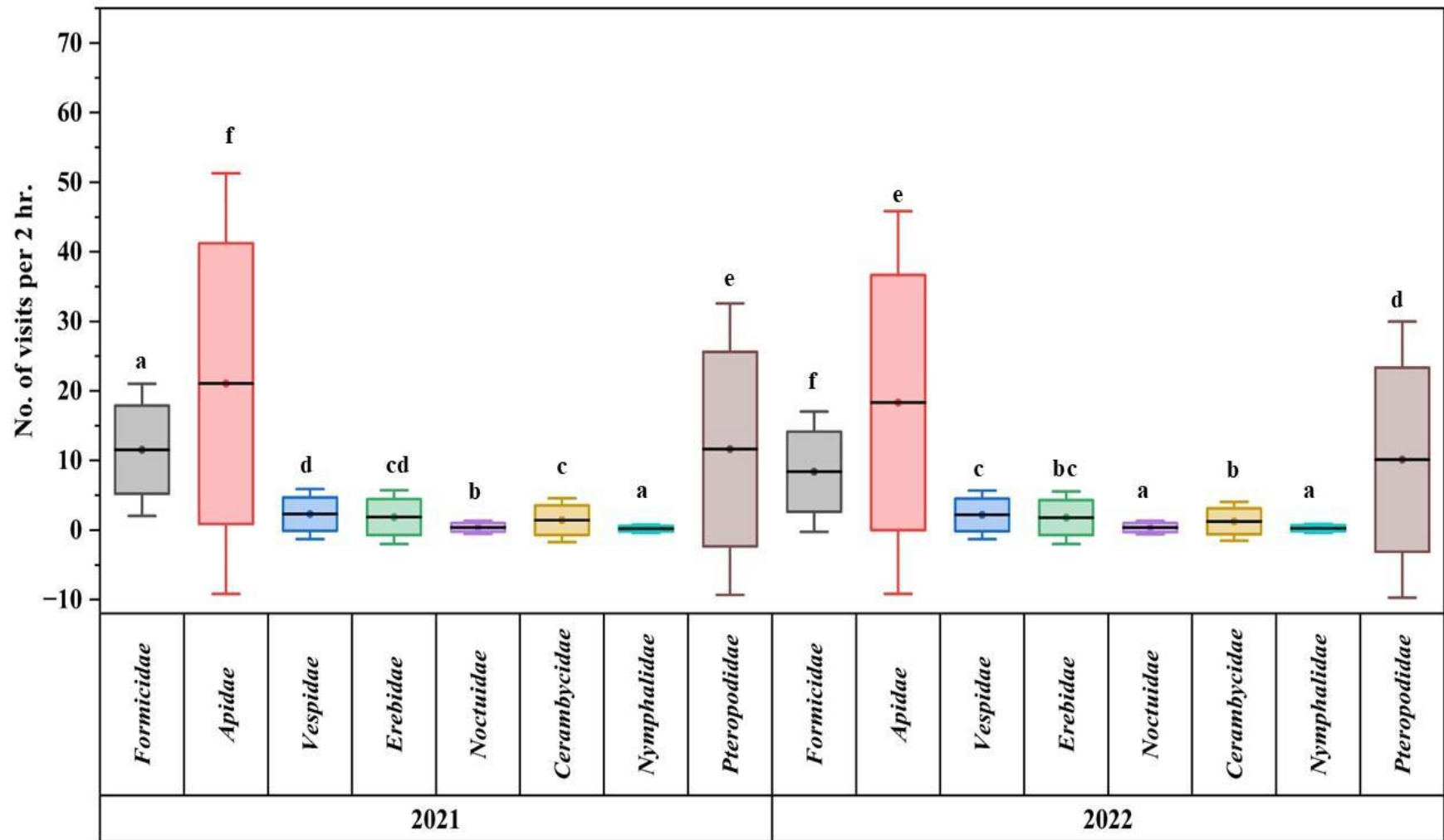


Figure 5.31. Visitation frequency of each pollinator for the year 2021 and 2022 as per family wise.

changes in visitation frequency may reflect broader environmental or ecological shifts, potentially influencing the foraging behavior of these families. Despite these reductions, Apidae and Pteropodidae continued to be the dominant pollinators, contributing significantly to the ecosystem's pollination services, while other families maintained lower levels of activity.

5.4.18. Visitation frequency of each pollinator for the year 2021 and 2022 as per order wise.

The visitation frequencies of pollinators from different orders in 2021 and 2022 reveal important insights into the temporal shifts and relative activity levels of key pollinator groups. In 2021, Hymenoptera, which encompasses bees, ants, and other related species, exhibited the highest visitation frequency at 34.89 visits per 2 hours, underscoring its critical role in pollination during this period (Figure 5.32.). This dominance was maintained in 2022, though visitation decreased slightly to 28.88 visits per 2 hours, suggesting a subtle decline in activity over the course of the year. The Lepidoptera order, which includes butterflies and moths, showed moderate levels of visitation, with 2.43 visits per 2 hours in 2021 and a slight decline to 2.38 visits per 2 hours in 2022. Coleoptera (beetles) exhibited low visitation levels, with 1.42 visits per 2 hours in 2021, which slightly decreased to 1.25 visits per 2 hours in 2022, indicating a stable yet minimal contribution to pollination (Figure 5.32.).

The Chiroptera order, represented by bats, displayed a notable level of activity, with 11.63 visits per 2 hours in 2021, reflecting their significant role in nocturnal pollination (Figure 5.32.). However, visitation by Chiroptera decreased in 2022 to 10.13 visits per 2 hours. This overall decline across multiple orders, particularly in Hymenoptera and Chiroptera, suggests potential ecological shifts, which could be linked to factors such as climate change, resource availability, or alterations in local biodiversity. Despite these reductions, Hymenoptera remained the most active order in both years, continuing to play a dominant role in pollination, while Chiroptera continued to contribute significantly to nocturnal pollination.

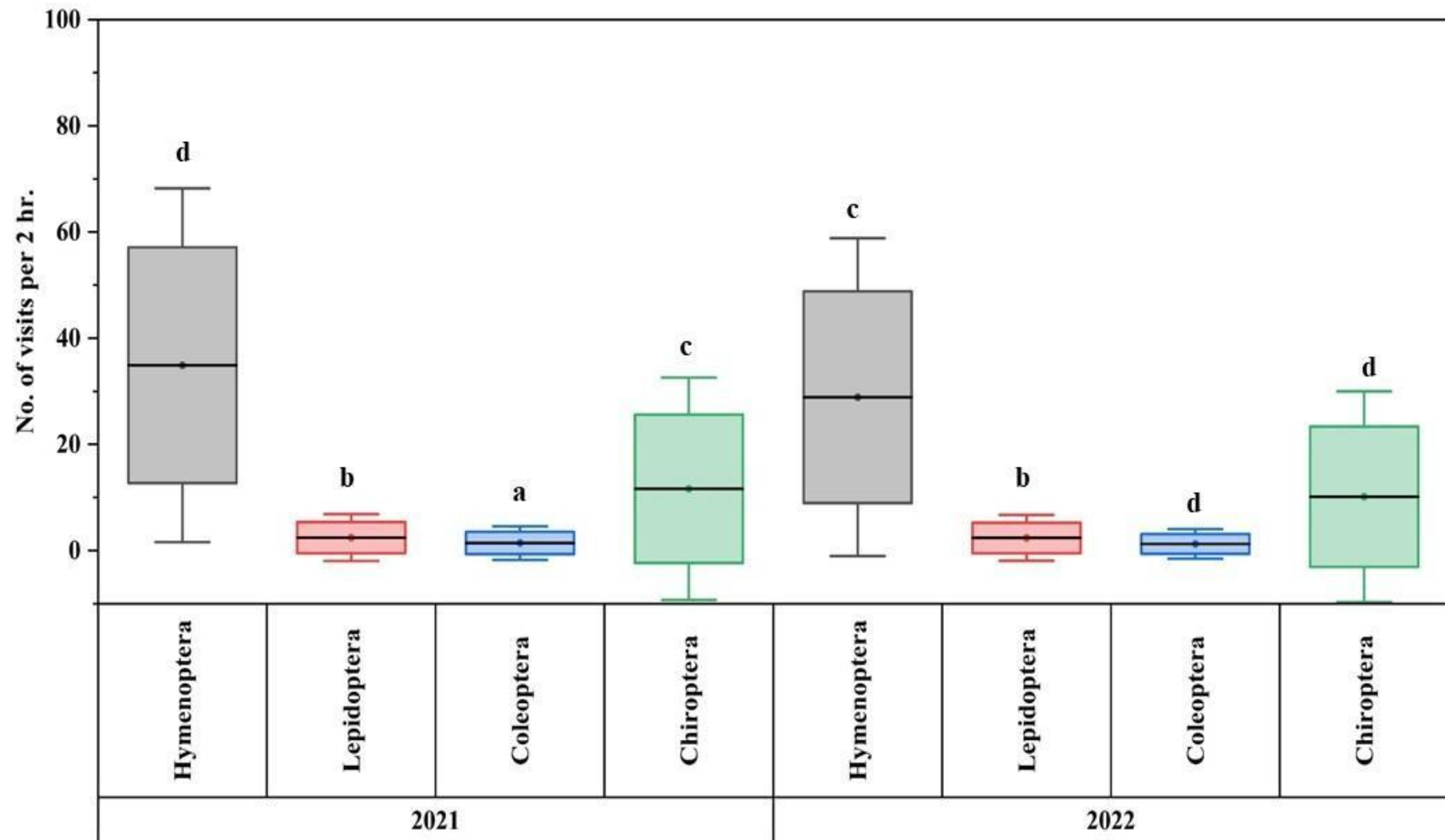


Figure 5.32. Visitation frequency of each pollinator for the year 2021 and 2022 as per order wise.

5.4.19. Spearman's rank correlation coefficient of pollinators and climatic variables

Spearman's rank correlation analysis conducted for the years 2021 and 2022 provided valuable insights into the relationships between pollinator activity and climatic variables. In 2021, significant negative correlations were observed between time (T) and several pollinator species, including *Camponotus* spp. ($r_s = -0.392^{**}$, $p < 0.01$) and *T. sessile* ($r_s = -0.485^{**}$, $p < 0.01$), suggesting that as time progressed, the activity of these species decreased (Table 5.11.). In contrast, *B. bicoloratus* and *A. cerana indica* exhibited positive correlations with time ($r_s = 0.313^{**}$, $p < 0.01$ and $r_s = 0.409^{**}$, $p < 0.01$, respectively), indicating that these species remained more active over time. Regarding temperature, both the temperature at 2 meters (TM) and dew point (TDEW) showed positive correlations with several pollinators, such as *Trigona* spp. ($r_s = 0.333^{**}$, $p < 0.01$) and *A. cerana indica* ($r_s = 0.802^{**}$, $p < 0.01$), highlighting the role of warmer conditions in supporting pollinator activity. Specific humidity (QV) was also positively correlated with pollinator activity, particularly for *V. affinis* ($r_s = 0.246^{**}$, $p < 0.01$) and *P. flavopictus* ($r_s = 0.334^{**}$, $p < 0.01$), while relative humidity (RH) exhibited a negative correlation with *B. bicoloratus* ($r_s = -0.375^{**}$, $p < 0.01$), suggesting that high humidity may negatively influence certain species (Table 5.11.).

In 2022, the correlation patterns remained consistent for many species. Temperature at 2 meters (TM) continued to negatively influence *Camponotus* spp. ($r_s = -0.440^{**}$, $p < 0.01$) and *T. sessile* ($r_s = -0.512^{**}$, $p < 0.01$), but it had a positive effect on *B. bicoloratus* ($r_s = 0.358^{**}$, $p < 0.01$) and *A. cerana indica* ($r_s = 0.393^{**}$, $p < 0.01$), supporting the idea that some pollinators thrive in warmer temperatures. Dew point (TDEW) and specific humidity (QV) again showed positive correlations with *Trigona* spp. ($r_s = 0.316^{**}$, $p < 0.01$) and *A. cerana indica* ($r_s = 0.797^{**}$, $p < 0.01$), further emphasizing the importance of moisture levels in sustaining pollinator activity. Additionally, wind speed (WS) exhibited significant negative correlations with several species, such as *B. bicoloratus* ($r_s = -0.379^{**}$, $p < 0.01$) and *A. cerana indica* ($r_s = -0.455^{**}$, $p < 0.01$), suggesting that high wind speeds may hinder pollinator movement and foraging (Table 5.12.). These results highlight the critical role of climatic factors,

Table 5.11. Spearman's rank correlation analysis between Time, *Camponotus spp.*, *Tapinoma sessile*, *Bombus bicoloratus*, *Apis cerana indica*, *Trigona spp.*, *Vespa affinis*, *Phimenes flavopictus*, *Achaea serva*, *Agrotis infusa*, *Ercheia cyllaria*, *Eudocima phalonia*, *Hulodes caranea*, *Psyrassa unicolor*, *Ariadne merione*, bat, and climatic variables for 2021.

	Time	<i>Camponotus spp.</i>	<i>Tapinoma sessile</i>	<i>Bombus bicoloratus</i>	<i>Apis cerana indica</i>
Time	1	-0.392**	-0.485**	0.313**	0.409**
	-	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Camponotus spp.</i>	-0.392**	1	0.824**	-0.023	0.015
	p = 0.000	-	p = 0.000	p = 0.802	p = 0.870
<i>Tapinoma sessile</i>	-0.485**	0.824**	1	-0.081	0.015
	p = 0.000	p = 0.000	-	p = 0.379	p = 0.867
<i>Bombus bicoloratus</i>	0.313**	-0.023	-0.081	1	0.832**
	p = 0.000	p = 0.802	p = 0.379	-	p = 0.000
<i>Apis cerana indica</i>	0.409**	0.015	0.015	0.832**	1
	p = 0.000	p = 0.870	p = 0.867	p = 0.000	-
<i>Trigona spp.</i>	0.333**	0.101	0.110	0.659**	0.802**
	p = 0.000	p = 0.270	p = 0.230	p = 0.000	p = 0.000
<i>Vespa affinis</i>	0.006	0.246**	0.266**	0.449**	0.470**
	p = 0.948	p = 0.007	p = 0.003	p = 0.000	p = 0.000
<i>Phimenes flavopictus</i>	0.063	0.296**	0.334**	0.422**	0.598**
	p = 0.492	p = 0.001	p = 0.000	p = 0.000	p = 0.000
<i>Achaea serva</i>	-0.524**	0.289**	0.373**	-0.605**	-0.645**
	p = 0.000	p = 0.001	p = 0.000	p = 0.000	p = 0.000
<i>Agrotis infusa</i>	-0.465**	0.148	0.213*	-0.590**	-0.655**
	p = 0.000	p = 0.106	p = 0.020	p = 0.000	p = 0.000
<i>Ercheia cyllaria</i>	-0.384**	0.129	0.176	-0.513**	-0.560**
	p = 0.000	p = 0.162	p = 0.055	p = 0.000	p = 0.000

<i>Eudocima phalonia</i>	−0.576** p = 0.000	0.352** p = 0.000	0.389** p = 0.000	−0.615** p = 0.000	−0.601** p = 0.000
<i>Hulodes caranea</i>	−0.574** p = 0.000	0.246** p = 0.007	0.273** p = 0.003	−0.623** p = 0.000	−0.715** p = 0.000
<i>Psyrassa unicolor</i>	−0.601** p = 0.000	0.276** p = 0.002	0.298** p = 0.001	−0.741** p = 0.000	−0.773** p = 0.000
<i>Ariadne merione</i>	0.402** p = 0.000	−0.123 p = 0.180	−0.202* p = 0.027	0.290** p = 0.001	0.402** p = 0.000
Bat	−0.617** p = 0.000	0.213* p = 0.019	0.246** p = 0.007	−0.752** p = 0.000	−0.824** p = 0.000
TM	0.217* p = 0.017	0.237** p = 0.009	0.182* p = 0.046	0.025 p = 0.786	0.174 p = 0.057
TDEW	−0.321** p = 0.000	0.522** p = 0.000	0.548** p = 0.000	−0.200* p = 0.029	−0.054 p = 0.559
TWET	0.110 p = 0.233	0.293** p = 0.001	0.241** p = 0.008	−0.003 p = 0.973	0.135 p = 0.141
QV	−0.317** p = 0.000	0.527** p = 0.000	0.551** p = 0.000	−0.197* p = 0.031	−0.051 p = 0.580
RH	−0.375** p = 0.000	−0.077 p = 0.405	−0.010 p = 0.912	−0.190* p = 0.037	−0.319** p = 0.000
PR	0.078 p = 0.400	−0.216* p = 0.018	−0.183* p = 0.045	0.145 p = 0.115	0.104 p = 0.259
WS	−0.381** p = 0.000	0.056 p = 0.547	0.083 p = 0.368	−0.379** p = 0.000	−0.455** p = 0.000

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

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

	<i>Trigona spp.</i>	<i>Vespa affinis</i>	<i>Phimenes flavopictus</i>	<i>Psyrrassa unicolor</i>	<i>Ariadne merione</i>
Time	0.333** p = 0.000	0.006 p = 0.948	0.063 p = 0.492	-0.601** p = 0.000	0.402** p = 0.000
<i>Camponotus spp.</i>	0.101 p = 0.270	0.246** p = 0.007	0.296** p = 0.001	0.276** p = 0.002	-0.123 p = 0.180
<i>Tapinoma sessile</i>	0.110 p = 0.230	0.266** p = 0.003	0.334** p = 0.000	0.298** p = 0.001	-0.202* p = 0.027
<i>Bombus bicoloratus</i>	0.659** p = 0.000	0.449** p = 0.000	0.422** p = 0.000	-0.741** p = 0.000	0.290** p = 0.001
<i>Apis cerana indica</i>	0.802** p = 0.000	0.470** p = 0.000	0.598** p = 0.000	-0.773** p = 0.000	0.402** p = 0.000
<i>Trigona spp.</i>	1 -	0.619** p = 0.000	0.760** p = 0.000	-0.753** p = 0.000	0.423** p = 0.000
<i>Vespa affinis</i>	0.619** p = 0.000	1 -	0.672** p = 0.000	-0.484** p = 0.000	0.269** p = 0.003
<i>Phimenes flavopictus</i>	0.760** p = 0.000	0.672** p = 0.000	1 -	-0.518** p = 0.000	0.254** p = 0.005
<i>Achaea serva</i>	-0.623** p = 0.000	-0.482** p = 0.000	-0.480** p = 0.000	0.829** p = 0.000	-0.337** p = 0.000
<i>Agrotis infusa</i>	-0.601** p = 0.000	-0.411** p = 0.000	-0.445** p = 0.000	0.760** p = 0.000	-0.328** p = 0.000
<i>Ercheia cyllaria</i>	-0.472** p = 0.000	-0.357** p = 0.000	-0.407** p = 0.000	0.683** p = 0.000	-0.261** p = 0.004
<i>Eudocima phalonia</i>	-0.541** p = 0.000	-0.317** p = 0.000	-0.353** p = 0.000	0.776** p = 0.000	-0.298** p = 0.001

<i>Hulodes caranea</i>	−0.622** p = 0.000	−0.450** p = 0.000	−0.483** p = 0.000	0.781** p = 0.000	−0.385** p = 0.000
<i>Psyrassa unicolor</i>	−0.753** p = 0.000	−0.484** p = 0.000	−0.518** p = 0.000	1 -	−0.417** p = 0.000
<i>Ariadne merione</i>	0.423** p = 0.000	0.269** p = 0.003	0.254** p = 0.005	−0.417** p = 0.000	1 -
Bat	−0.817** p = 0.000	−0.545** p = 0.000	−0.590** p = 0.000	0.950** p = 0.000	−0.451** p = 0.000
TM	0.510** p = 0.000	0.492** p = 0.000	0.505** p = 0.000	−0.324** p = 0.000	0.384** p = 0.000
TDEW	0.253** p = 0.005	0.380** p = 0.000	0.413** p = 0.000	0.127 p = 0.168	0.172 p = 0.061
TWET	0.485** p = 0.000	0.510** p = 0.000	0.508** p = 0.000	−0.271** p = 0.003	0.346** p = 0.000
QV	0.256** p = 0.005	0.388** p = 0.000	0.419** p = 0.000	0.117 0.204	0.162 0.078
RH	−0.556** p = 0.000	−0.462** p = 0.000	−0.490** p = 0.000	0.480** p = 0.000	−0.413** p = 0.000
PR	0.149 p = 0.104	0.174 p = 0.057	0.177 p = 0.053	−0.255** p = 0.005	0.150 p = 0.102
WS	−0.665** p = 0.000	−0.495** p = 0.000	−0.507** p = 0.000	0.631** p = 0.000	−0.366** p = 0.000

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

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

	<i>Achaea serva</i>	<i>Agrotis infusa</i>	<i>Ercheia cyllaria</i>	<i>Eudocima phalonia</i>	<i>Hulodes caranea</i>	Bat
Time	-0.524** p = 0.000	-0.465** p = 0.000	-0.384** p = 0.000	-0.576** p = 0.000	-0.574** p = 0.000	-0.617** p = 0.000
<i>Camponotus spp.</i>	0.289** p = 0.001	0.148 p = 0.106	0.129 p = 0.162	0.352** p = 0.000	0.246** p = 0.007	0.213* p = 0.019
<i>Tapinoma sessile</i>	0.373** p = 0.000	0.213* p = 0.020	0.176 p = 0.055	0.389** p = 0.000	0.273** p = 0.003	0.246** p = 0.007
<i>Bombus bicoloratus</i>	-0.605** p = 0.000	-0.590** p = 0.000	-0.513** p = 0.000	-0.615** p = 0.000	-0.623** p = 0.000	-0.752** p = 0.000
<i>Apis cerana indica</i>	-0.645** p = 0.000	-0.655** p = 0.000	-0.560** p = 0.000	-0.601** p = 0.000	-0.715** p = 0.000	-0.824** p = 0.000
<i>Trigona spp.</i>	-0.623** p = 0.000	-0.601** p = 0.000	-0.472** p = 0.000	-0.541** p = 0.000	-0.622** p = 0.000	-0.817** p = 0.000
<i>Vespa affinis</i>	-0.482** p = 0.000	-0.411** p = 0.000	-0.357** p = 0.000	-0.317** p = 0.000	-0.450** p = 0.000	-0.545** p = 0.000
<i>Phimenes flavopictus</i>	-0.480** p = 0.000	-0.445** p = 0.000	-0.407** p = 0.000	-0.353** p = 0.000	-0.483** p = 0.000	-0.590** p = 0.000
<i>Achaea serva</i>	1 -	0.683** p = 0.000	0.650** p = 0.000	0.769** p = 0.000	0.746** p = 0.000	0.838** p = 0.000
<i>Agrotis infusa</i>	0.683** p = 0.000	1 -	0.543** p = 0.000	0.680** p = 0.000	0.701** p = 0.000	0.784** p = 0.000
<i>Ercheia cyllaria</i>	0.650** p = 0.000	0.543** p = 0.000	1 -	0.511** p = 0.000	0.673** p = 0.000	0.666** p = 0.000
<i>Eudocima phalonia</i>	0.769** p = 0.000	0.680** p = 0.000	0.511** p = 0.000	1 -	0.609** p = 0.000	0.769** p = 0.000
<i>Hulodes caranea</i>	0.746** p = 0.000	0.701** p = 0.000	0.673** p = 0.000	0.609** p = 0.000	1 -	0.843** p = 0.000

<i>Psyrassa unicolor</i>	0.829** p = 0.000	0.760** p = 0.000	0.683** p = 0.000	0.776** p = 0.000	0.781** p = 0.000	0.950** p = 0.000
<i>Ariadne merione</i>	-0.337** p = 0.000	-0.328** p = 0.000	-0.261** p = 0.004	-0.298** p = 0.001	-0.385** p = 0.000	-0.451** p = 0.000
Bat	0.838** p = 0.000	0.784** p = 0.000	0.666** p = 0.000	0.769** p = 0.000	0.843** p = 0.000	1 -
TM	-0.227* p = 0.013	-0.267** p = 0.003	-0.226* p = 0.013	-0.149 p = 0.104	-0.272** p = 0.003	-0.390** p = 0.000
TDEW	0.157 p = 0.087	0.098 p = 0.285	0.032 p = 0.730	0.258** p = 0.004	0.130 p = 0.157	0.079 p = 0.389
TWET	-0.184* p = 0.044	-0.220* p = 0.016	-0.200* p = 0.028	-0.092 p = 0.317	-0.217* p = 0.017	-0.333** p = 0.000
QV	0.147 p = 0.110	0.086 p = 0.348	0.017 p = 0.855	0.253** p = 0.005	0.119 p = 0.196	0.069 p = 0.452
RH	0.376** p = 0.000	0.449** p = 0.000	0.301** p = 0.001	0.317** p = 0.000	0.418** p = 0.000	0.552** p = 0.000
PR	-0.299** p = 0.001	-0.161 p = 0.078	-0.133 p = 0.149	-0.257** p = 0.005	-0.135 p = 0.142	-0.240** p = 0.008
WS	0.549** p = 0.000	0.466** p = 0.000	0.422** p = 0.000	0.458** p = 0.000	0.545** p = 0.000	0.646** p = 0.000

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Table 5.12. Spearman's rank correlation analysis between Time, *Camponotus spp.*, *Tapinoma sessile*, *Bombus bicoloratus*, *Apis cerana indica*, *Trigona spp.*, *Vespa affinis*, *Phimenes flavopictus*, *Achaea serva*, *Agrotis infusa*, *Ercheia cyllaria*, *Eudocima phalonia*, *Hulodes caranea*, *Psyrassa unicolor*, *Ariadne merione*, bat, and climatic variables for 2022.

	Time	<i>Camponotus spp.</i>	<i>Tapinoma sessile</i>	<i>Bombus bicoloratus</i>	<i>Apis cerana indica</i>
Time	1	−0.440**	−0.512**	0.358**	0.393**
	-	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Camponotus spp.</i>	−0.440**	1	0.644**	−0.197*	−0.087
	p = 0.000	-	p = 0.000	p = 0.031	p = 0.346
<i>Tapinoma sessile</i>	−0.512**	0.644**	1	−0.082	0.022
	p = 0.000	p = 0.000	-	p = 0.373	p = 0.808
<i>Bombus bicoloratus</i>	0.358**	−0.197*	−0.082	1	0.883**
	p = 0.000	0.031	0.373	-	p = 0.000
<i>Apis cerana indica</i>	0.393**	−0.087	0.022	0.883**	1
	p = 0.000	p = 0.346	p = 0.808	p = 0.000	-
<i>Trigona spp.</i>	0.316**	0.009	0.198*	0.732**	0.797**
	p = 0.000	p = 0.924	p = 0.031	p = 0.000	p = 0.000
<i>Vespa affinis</i>	0.072	0.138	0.322**	0.454**	0.551**
	p = 0.432	p = 0.134	p = 0.000	p = 0.000	p = 0.000
<i>Phimenes flavopictus</i>	p = 0.000	0.156	0.348**	0.455**	0.617**
	p = 0.997	p = 0.088	p = 0.000	p = 0.000	p = 0.000
<i>Achaea serva</i>	−0.522**	0.362**	0.335**	−0.637**	−0.638**
	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Agrotis infusa</i>	−0.426**	0.252**	0.146	−0.590**	−0.629**
	p = 0.000	p = 0.006	p = 0.113	p = 0.000	p = 0.000
<i>Ercheia cyllaria</i>	−0.433**	0.297**	0.246**	−0.585**	−0.579**
	p = 0.000	p = 0.001	p = 0.007	p = 0.000	p = 0.000

<i>Eudocima phalonia</i>	−0.570** p = 0.000	0.462** p = 0.000	0.388** p = 0.000	−0.667** p = 0.000	−0.604** p = 0.000
<i>Hulodes caranea</i>	−0.571** p = 0.000	0.363** p = 0.000	0.280** p = 0.002	−0.671** p = 0.000	−0.697** p = 0.000
<i>Psyrassa unicolor</i>	−0.593** p = 0.000	0.384** p = 0.000	0.281** p = 0.002	−0.786** p = 0.000	−0.762** p = 0.000
<i>Ariadne merione</i>	0.398** p = 0.000	−0.135 p = 0.141	−0.06 p = 0.514	0.363** p = 0.000	0.418** p = 0.000
Bat	−0.611** p = 0.000	0.307** p = 0.001	0.205* p = 0.025	−0.807** p = 0.000	−0.806** p = 0.000
TM	0.159 p = 0.083	0.024 p = 0.793	0.284** p = 0.002	0.073 p = 0.428	0.119 p = 0.197
TDEW	−0.362** p = 0.000	0.361** p = 0.000	0.590** p = 0.000	−0.192* p = 0.035	−0.055 p = 0.549
TWET	0.053 p = 0.568	0.076 p = 0.408	0.353** p = 0.000	0.039 p = 0.674	0.088 p = 0.339
QV	−0.362** p = 0.000	0.350** p = 0.000	0.578** p = 0.000	−0.189* p = 0.038	−0.057 p = 0.538
RH	−0.257** p = 0.005	0.046 p = 0.619	−0.153 p = 0.095	−0.144 p = 0.116	−0.161 p = 0.079
PR	−0.131 p = 0.155	−0.027 p = 0.766	0.018 p = 0.846	−0.062 p = 0.498	−0.136 p = 0.139
WS	−0.420** p = 0.000	0.175 p = 0.056	0.041 p = 0.656	−0.571** p = 0.000	−0.589** p = 0.000

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

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

	<i>Trigona spp.</i>	<i>Vespa affinis</i>	<i>Phimenes flavopictus</i>	<i>Psyrrassa unicolor</i>	<i>Ariadne merione</i>
Time	0.398** p = 0.000	0.072 p = 0.432	0 p = 0.997	-0.593** p = 0.000	0.398** p = 0.000
<i>Camponotus spp.</i>	-0.135 p = 0.141	0.138 p = 0.134	0.156 p = 0.088	0.384** p = 0.000	-0.135 p = 0.141
<i>Tapinoma sessile</i>	-0.06 p = 0.514	0.322** p = 0.000	0.348** p = 0.000	0.281** p = 0.002	-0.06 p = 0.514
<i>Bombus bicoloratus</i>	0.363** p = 0.000	0.454** p = 0.000	0.455** p = 0.000	-0.786** p = 0.000	0.363** p = 0.000
<i>Apis cerana indica</i>	0.418** p = 0.000	0.551** p = 0.000	0.617** p = 0.000	-0.762** p = 0.000	0.418** p = 0.000
<i>Trigona spp.</i>	0.536** p = 0.000	0.676** p = 0.000	0.733** p = 0.000	-0.706** p = 0.000	0.536** p = 0.000
<i>Vespa affinis</i>	0.321** p = 0.000	1 -	0.699** p = 0.000	-0.540** p = 0.000	0.321** p = 0.000
<i>Phimenes flavopictus</i>	0.345** p = 0.000	0.699** p = 0.000	1 -	-0.489** p = 0.000	0.345** p = 0.000
<i>Achaea serva</i>	-0.384** p = 0.000	-0.495** p = 0.000	-0.453** p = 0.000	0.855** p = 0.000	-0.384** p = 0.000
<i>Agrotis infusa</i>	-0.345** p = 0.000	-0.407** p = 0.000	-0.390** p = 0.000	0.682** p = 0.000	-0.345** p = 0.000
<i>Ercheia cyllaria</i>	-0.323** p = 0.000	-0.427** p = 0.000	-0.392** p = 0.000	0.756** p = 0.000	-0.323** p = 0.000
<i>Eudocima phalonia</i>	-0.348** p = 0.000	-0.368** p = 0.000	-0.300** p = 0.001	0.787** p = 0.000	-0.348** p = 0.000

<i>Hulodes caranea</i>	−0.414** p = 0.000	−0.470** p = 0.000	−0.477** p = 0.000	0.834** p = 0.000	−0.414** p = 0.000
<i>Psyrassa unicolor</i>	−0.469** p = 0.000	−0.540** p = 0.000	−0.489** p = 0.000	1 -	−0.469** p = 0.000
<i>Ariadne merione</i>	1 -	0.321** p = 0.000	0.345** p = 0.000	−0.469** p = 0.000	1 -
Bat	−0.523** p = 0.000	−0.602** p = 0.000	−0.565** p = 0.000	0.934** p = 0.000	−0.523** p = 0.000
TM	0.411** p = 0.000	0.471** p = 0.000	0.442** p = 0.000	−0.250** p = 0.006	0.411** p = 0.000
TDEW	0.180* p = 0.05	0.315** p = 0.000	0.350** p = 0.000	0.210* p = 0.021	0.180* p = 0.05
TWET	0.387** p = 0.000	0.497** p = 0.000	0.466** p = 0.000	−0.195* p = 0.033	0.387** p = 0.000
QV	0.181* p = 0.048	0.315** p = 0.000	0.349** p = 0.000	0.206* p = 0.024	0.181* p = 0.048
RH	−0.372** p = 0.000	−0.410** p = 0.000	−0.375** p = 0.000	0.318** p = 0.000	−0.372** p = 0.000
PR	0.017 p = 0.853	0.044 p = 0.631	−0.103 p = 0.264	0.077 p = 0.404	0.017 p = 0.853
WS	−0.469** p = 0.000	−0.633** p = 0.000	−0.566** p = 0.000	0.716** p = 0.000	−0.469** p = 0.000

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

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

	<i>Achaea serva</i>	<i>Agrotis infusa</i>	<i>Ercheia cyllaria</i>	<i>Eudocima phalonia</i>	<i>Hulodes caranea</i>	Bat
Time	−0.522**	−0.426**	−0.433**	−0.570**	−0.571**	−0.611**
	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Camponotus spp.</i>	0.362**	0.252**	0.297**	0.462**	0.363**	0.307**
	p = 0.000	p = 0.006	p = 0.001	p = 0.000	p = 0.000	p = 0.001
<i>Tapinoma sessile</i>	0.335**	0.146	0.246**	0.388**	0.280**	0.205*
	p = 0.000	p = 0.113	p = 0.007	p = 0.000	p = 0.002	p = 0.025
<i>Bombus bicoloratus</i>	−0.637**	−0.590**	−0.585**	−0.667**	−0.671**	−0.807**
	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Apis cerana indica</i>	−0.638**	−0.629**	−0.579**	−0.604**	−0.697**	−0.806**
	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Trigona spp.</i>	−0.591**	−0.510**	−0.471**	−0.524**	−0.617**	−0.799**
	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Vespa affinis</i>	−0.495**	−0.407**	−0.427**	−0.368**	−0.470**	−0.602**
	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Phimenes flavopictus</i>	−0.453**	−0.390**	−0.392**	−0.300**	−0.477**	−0.565**
	p = 0.000	p = 0.000	p = 0.000	0.001	p = 0.000	p = 0.000
<i>Achaea serva</i>	1	0.695**	0.693**	0.799**	0.761**	0.844**
	-	p = 0.000	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Agrotis infusa</i>	0.695**	1	0.605**	0.669**	0.646**	0.711**
	p = 0.000	-	p = 0.000	p = 0.000	p = 0.000	p = 0.000
<i>Ercheia cyllaria</i>	0.693**	0.605**	1	0.618**	0.736**	0.746**
	p = 0.000	p = 0.000	-	p = 0.000	p = 0.000	p = 0.000
<i>Eudocima phalonia</i>	0.799**	0.669**	0.618**	1	0.710**	0.776**
	p = 0.000	p = 0.000	p = 0.000	-	p = 0.000	p = 0.000

<i>Hulodes caranea</i>	0.761** p = 0.000	0.646** p = 0.000	0.736** p = 0.000	0.710** p = 0.000	1 -	0.835** p = 0.000
<i>Psyrrassa unicolor</i>	0.855** p = 0.000	0.682** p = 0.000	0.756** p = 0.000	0.787** p = 0.000	0.834** p = 0.000	0.934** p = 0.000
<i>Ariadne merione</i>	-0.384** p = 0.000	-0.345** p = 0.000	-0.323** p = 0.000	-0.348** p = 0.000	-0.414** p = 0.000	-0.523** p = 0.000
Bat	0.844** p = 0.000	0.711** p = 0.000	0.746** p = 0.000	0.776** p = 0.000	0.835** p = 0.000	1 -
TM	-0.147 p = 0.108	-0.224* p = 0.014	-0.177 p = 0.054	-0.126 p = 0.169	-0.235** p = 0.01	-0.353** p = 0.000
TDEW	0.267** p = 0.003	0.134 p = 0.144	0.149 p = 0.105	0.274** p = 0.002	0.141 p = 0.125	0.127 p = 0.167
TWET	-0.1 p = 0.279	-0.169 p = 0.065	-0.14 p = 0.126	-0.075 p = 0.413	-0.191* p = 0.037	-0.299** p = 0.001
QV	0.261** p = 0.004	0.132 p = 0.152	0.146 p = 0.113	0.262** p = 0.004	0.134 p = 0.146	0.124 p = 0.177
RH	0.236** p = 0.01	0.342** p = 0.000	0.223* p = 0.014	0.229* p = 0.012	0.259** p = 0.004	0.409** p = 0.000
PR	0.082 p = 0.374	0.210* p = 0.021	0.041 p = 0.658	0.056 p = 0.541	0.078 p = 0.400	0.093 p = 0.315
WS	0.570** p = 0.000	0.438** p = 0.000	0.543** p = 0.000	0.519** p = 0.000	0.694** p = 0.000	0.744** p = 0.000

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

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

such as temperature, humidity, and wind speed, in influencing pollinator activity. By understanding these relationships, we can better predict how changing climatic conditions may impact pollination services, which are crucial for ecosystem health and agricultural productivity. The findings from both years suggest that optimal climatic conditions characterized by moderate temperatures, adequate humidity, and low wind speeds are essential for maximizing pollinator activity and ensuring efficient pollination processes.

5.5. Mating system

5.5.1. Fruit formation % of autogamy, open pollination, geitonogamy, and xenogamy in 2021, 2022, and 2023

The fruit formation percentages for different pollination methods, including autogamous self-pollination (autogamy), natural pollination (open pollination), geitonogamy, and xenogamy, varied significantly across the years 2021, 2022, and 2023. For autogamous self-pollination, no fruit formation was recorded in any of the years, with a consistent 0% in 2021, 2022, and 2023, indicating that this pollination method was ineffective in promoting fruit set during the study period. In contrast, natural pollination demonstrated a clear positive trend in fruit formation over time. Starting at 72.67% in 2021, natural pollination increased to 88.67% in 2022, and further rose to 90.67% in 2023, accompanied by a decrease in variability, suggesting an increasingly reliable contribution of natural pollinators to fruit formation over the years (Figure 5.33.).

Geitonogamy, involving pollination within the same plant, also showed an upward trajectory in fruit formation. In 2021, geitonogamy resulted in 14.67% fruit formation, which increased to 30.00% in 2022, and further reached 33.33% in 2023 (Figure 5.33.). This indicates that while geitonogamy contributed less to fruit set compared to natural pollination, its role in reproductive success was gradually increasing. Similarly, xenogamy, which involves cross-pollination between different plants, also exhibited a gradual increase in fruit formation. Starting at 19.33% in 2021, xenogamy increased to 36.67% in 2022, and peaked at 38.00% in 2023, reflecting a steady rise in its

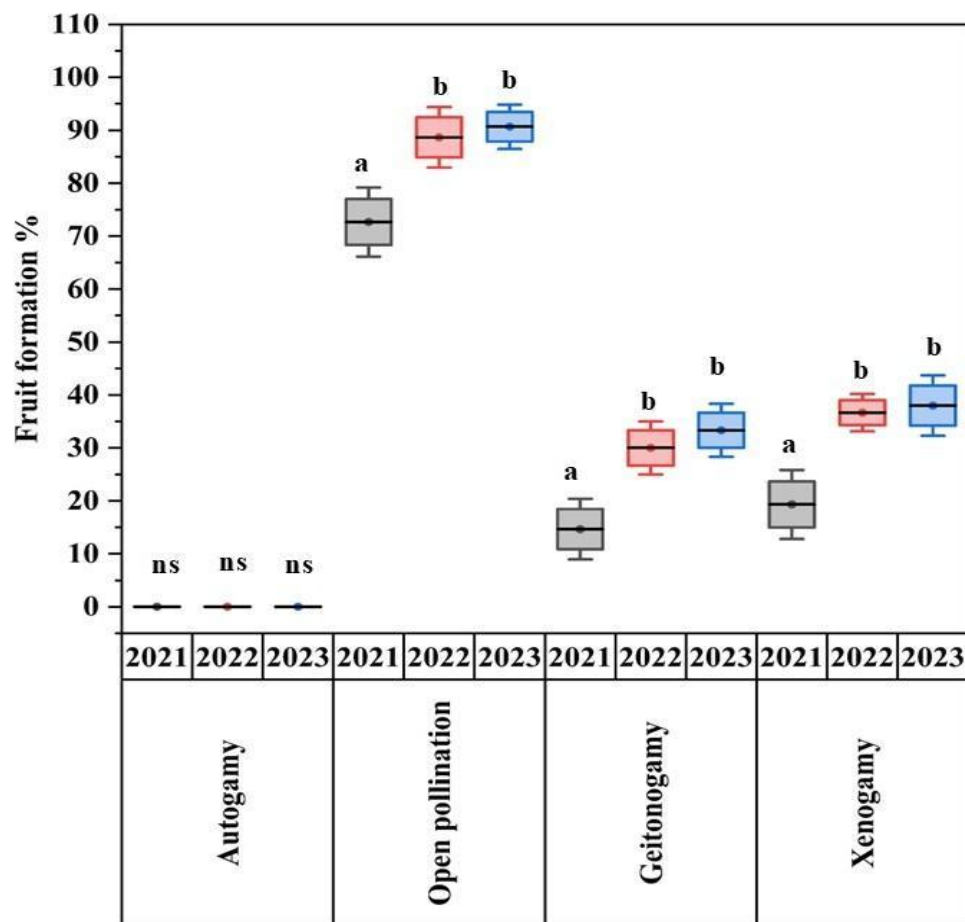


Figure 5.33. Fruit formation % of autogamy, open pollination, geitonogamy, and xenogamy in 2021, 2022, and 2023.

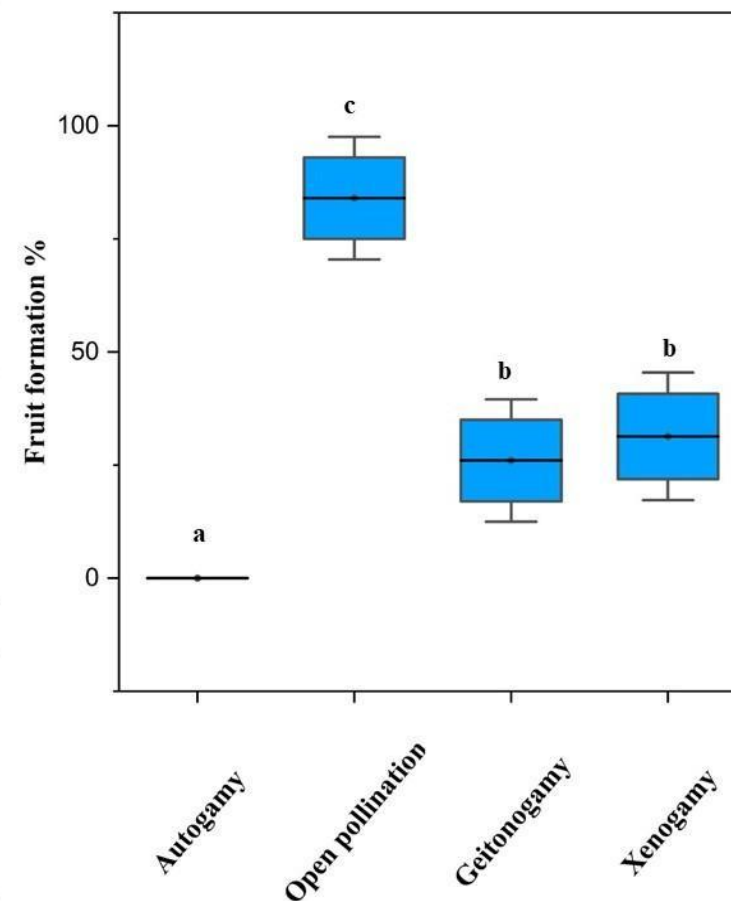


Figure 5.34. Effect of mating systems (autogamy, open pollination, geitonogamy, and xenogamy) on fruit formation in 2021, 2022, and 2023.

contribution to fruit set over the study period (Figure 5.33.). These findings emphasize the critical role of natural and cross-pollination methods in enhancing fruit formation, while autogamy did not contribute to fruit set in this context. The increasing fruit formation observed in both geitonogamy and xenogamy over time may reflect changes in environmental conditions or pollinator availability, which warrants further investigation. Overall, the data highlight the importance of optimizing pollination strategies to improve reproductive success and inform future agricultural practices.

5.5.2. Effect of mating systems (autogamy, open pollination, geitonogamy, and xenogamy) on fruit formation.

The influence of different mating systems on fruit formation was evaluated across autogamous self-pollination (autogamy), natural pollination (open pollination), geitonogamy, and xenogamy in 2021, 2022, and 2023, revealing distinct patterns in pollination success. Autogamous self-pollination resulted in no fruit formation, with a mean fruit formation percentage of 0.00%, indicating that self-pollination did not contribute to the reproductive success of the studied species. In contrast, natural pollination showed the highest efficacy, with a mean fruit formation percentage of 84.00%. This finding emphasizes the critical role of natural pollinators, likely including various insects and other pollinators, in promoting fruit set in the species examined. Geitonogamy, the process of pollination within the same tree, yielded a moderate fruit formation rate of 26.00%, suggesting that while this method contributes to reproductive success, it is not as effective as natural pollination (Figure 5.34.). Xenogamy, which involves cross-pollination between different trees, showed a slightly higher fruit formation rate of 31.33%, although still significantly lower than natural pollination (Figure 5.34.). Both geitonogamy and xenogamy exhibited relatively high variability, as evidenced by their standard deviations (9.01 and 9.41, respectively), indicating that these methods are less reliable in promoting fruit formation compared to natural pollination. These results underscore the superiority of natural pollination for fruit set, while also highlighting the potential but inconsistent contributions of cross-pollination strategies, such as geitonogamy and xenogamy. The study calls for further exploration of the ecological factors influencing these mating

systems and their implications for enhancing reproductive success in both natural and agricultural settings.

5.6. Relative contribution of nocturnal and diurnal pollinators to the reproductive success of *P. timoriana*

A total of 941 pods were collected, with 457 (48.57%) categorized as open, 395 (41.98%) as nocturnal, and 89 (9.46%) as diurnally pollinated. No pod production was observed in the pollinator exclusion treatment, suggesting the absence of spontaneous auto-fertilization. Seed length varied significantly across pollination treatments, except between nocturnal and open pollination, where no significant difference was observed at the 0.05 significance level. Seed lengths ranged from 21.13 mm to 18.00 mm, with a mean of 19.59 ± 0.69 mm. The largest seeds were found in the combined nocturnal and diurnal pollination (open pollination) treatment, followed by nocturnal pollination (18.85 ± 0.73 mm, 3.79% smaller), and diurnal pollination (17.67 ± 1.04 mm, 9.78% smaller) (Figure 5.35). The total number of pods per capitulum and seeds per pod exhibited significant differences between nocturnal and diurnal pollination treatments at the 0.05 level, but no significant differences were found between nocturnal and open treatments. Open pollination resulted in the highest total number of seeds per pod (20.55 ± 3.09) and seed weight (868.56 ± 181.61 mg) (Figure 5.35). Diurnal pollination yielded 12.95 ± 4.77 seeds per pod (36.98% lower) and seed weight of 694.45 ± 120.11 mg (20.05% reduction compared to open pollination), while nocturnal pollination produced 20.05 ± 3.19 seeds per pod (0.243% lower) and 793.95 ± 149.68 mg seed weight (8.59% reduction compared to open pollination). No significant differences were observed in seed diameter across open and nocturnal pollination, diurnal and nocturnal pollination, or open and diurnal pollination treatments at the 0.05 level. However, the average seed diameter was largest in the open pollination treatment (12.57 ± 1.88 mm), followed by nocturnal pollination (12.21 ± 1.31 mm), and diurnal pollination (11.79 ± 1.12 mm) (Figure 5.35). Significant differences were noted in the total number of pods per capitulum between treatments at the 0.05 level, except between open and nocturnal pollination. Open pollination recorded the highest number of pods per capitulum (22.85 ± 4.86), with

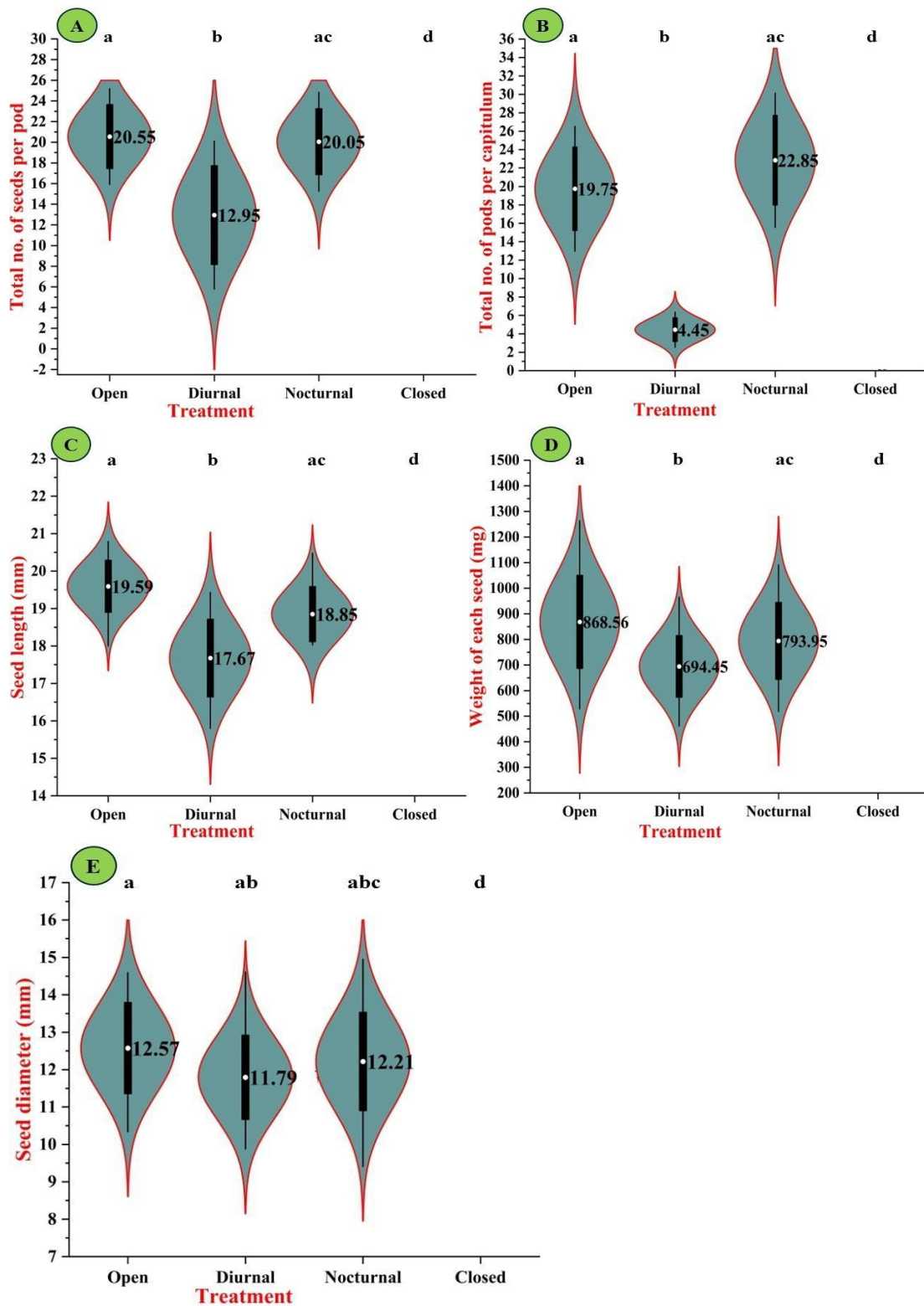


Figure 5.35. A. Total no. of seeds per pod, B. Total no. of pods per capitulum, C. Seed lengths (mm), D. Weight of each seed (mg), and E. Seed diameter (mm) produced by each pollination treatment during the bagging experiment. Means are shown with bold number. The same letters are not significantly different from each other (Kruskal-Wallis test at the $p < 0.05$ level).

nocturnal pollination showing a 13.57% reduction (19.75 ± 4.52), and diurnal pollination exhibiting an 80.53% reduction (4.45 ± 1.28) (Figure 5.35).

Spearman's rank correlation coefficient indicated moderate positive and statistically significant correlations between the total number of seeds per pod and total number of pods per capitulum ($r_s = 0.519^{**}$, $p < 0.01$); strong positive and statistically significant correlations between seed length and seed weight ($r_s = 0.697^{**}$, $p < 0.01$); weak positive and statistically significant correlations between seed length and seed diameter ($r_s = 0.291^*$, $p < 0.05$); and moderate positive and statistically significant correlations between seed weight and seed diameter ($r_s = 0.591^{**}$, $p < 0.01$) (Table 5.13). Negative correlations were observed between seed length and total number of seeds per pod, seed diameter and total number of seeds per pod, seed length and total number of pods per capitulum, seed weight and total number of pods per capitulum, and seed diameter and total number of pods per capitulum.

Table 5.13. Spearman's rank correlation coefficient between total no. of seeds per pod, total no. of pods per capitulum, seed length, weight of each seed, and seed diameter.

	Total no. of seeds per pod	Total no. of pods per capitulum	Seed length	Weight of each seed	Seed diameter
Total no. of seeds per pod	1				
	-				
Total no. of pods per capitulum	0.519** p = 0.000	1 -			
Seed length	-0.003 p = 0.981	-0.151 p = 250	1 -		
Weight of each seed	0.076 p = 0.566	-0.093 p = 0.482	0.697** p = 0.000	1 -	
Seed diameter	-0.023 p = 0.862	-0.193 p = 0.140	0.291* p = 0.024	0.591** p = 0.000	1 -
** Correlation is significant at the 0.01 level (2-tailed).					
* Correlation is significant at the 0.05 level (2-tailed).					

5.7. Pollen production, pollen-ovule ratio and pollen volume

5.7.1. Pollen production and pollen ovule ratio

5.7.1.1. Effect of sites on pollen production and pollen ovule ratio

5.7.1.1.1. No. of inflorescences per tree

The number of inflorescences per tree was monitored over three consecutive years (2021–2023) at three distinct sites: Sairang, Tanhril, and Reiek, located at varying altitudes. In 2021, Tanhril exhibited the highest mean inflorescence count per tree at 591.13 ± 83.97 , indicating considerable intra-site variability. In contrast, Sairang and Reiek had lower mean values of 435.07 ± 46.66 and 412.93 ± 26.85 , respectively, with relatively smaller standard deviations suggesting more consistent inflorescence production within these sites (Figure 5.36.). Statistical analysis revealed a significant difference in inflorescence production between Tanhril and both Sairang and Reiek ($p < 0.01$), whereas no significant difference was observed between Sairang and Reiek at the 0.01 significance level. In 2022, the mean number of inflorescences per tree declined at both Sairang (421.00 ± 26.90) and Tanhril (578.00 ± 37.40), while Reiek showed a slight increase to 443.80 ± 26.32 (Figure 5.36.). These shifts suggest that ecological or environmental factors may have influenced inflorescence production in specific locations, with the differing altitudes potentially playing a role. Statistical analysis for 2022 confirmed a significant difference in inflorescence production between all three sites ($p < 0.01$), highlighting the impact of altitude and other local conditions on inflorescence dynamics. By 2023, inflorescence production had increased in Sairang to 445.13 ± 44.85 and in Reiek to 485.07 ± 29.55 , while Tanhril maintained the highest mean count at 595.00 ± 39.95 (Figure 5.36.). A similar pattern of significant differences between all three sites was observed in 2023 ($p < 0.01$). These findings indicate a general trend of stabilization or increase in inflorescence production over time, with Tanhril consistently exhibiting the highest levels of variation. The variation in inflorescence counts across sites may reflect sensitivity to environmental changes, with Tanhril, located at a mid-altitude, showing higher

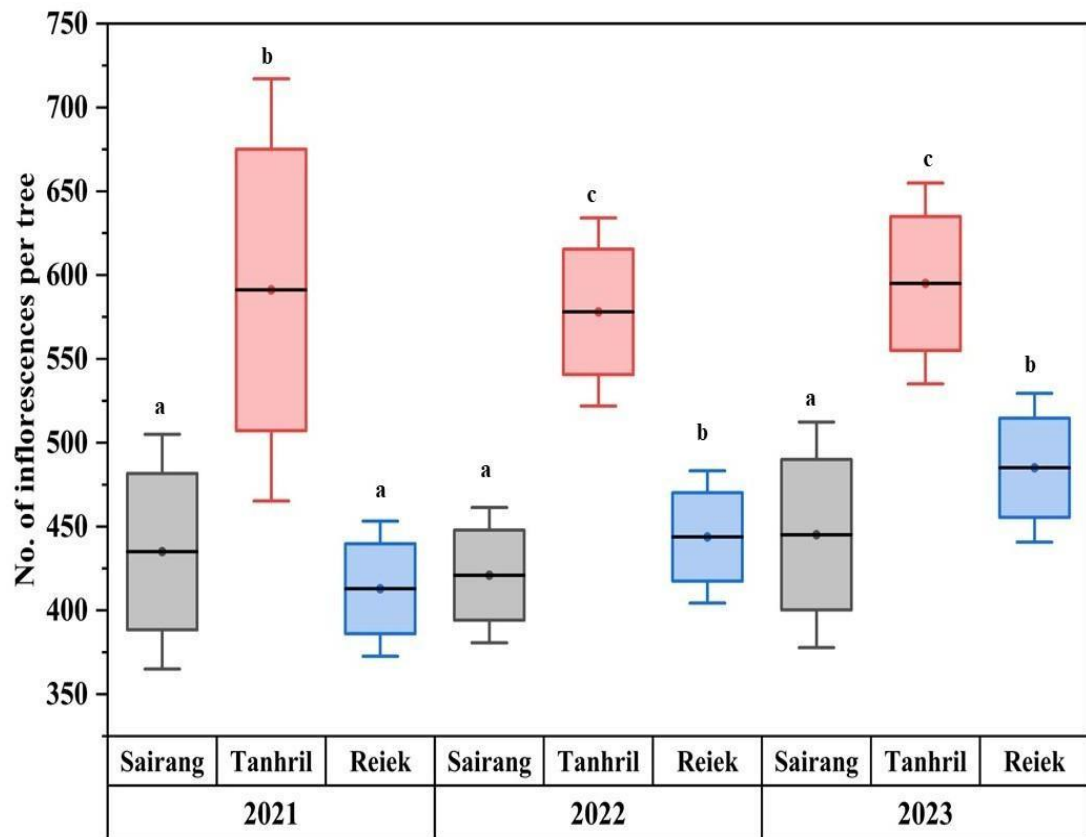


Figure 5.36. No. of inflorescences per tree for three sites in 2021, 2022 and 2023.

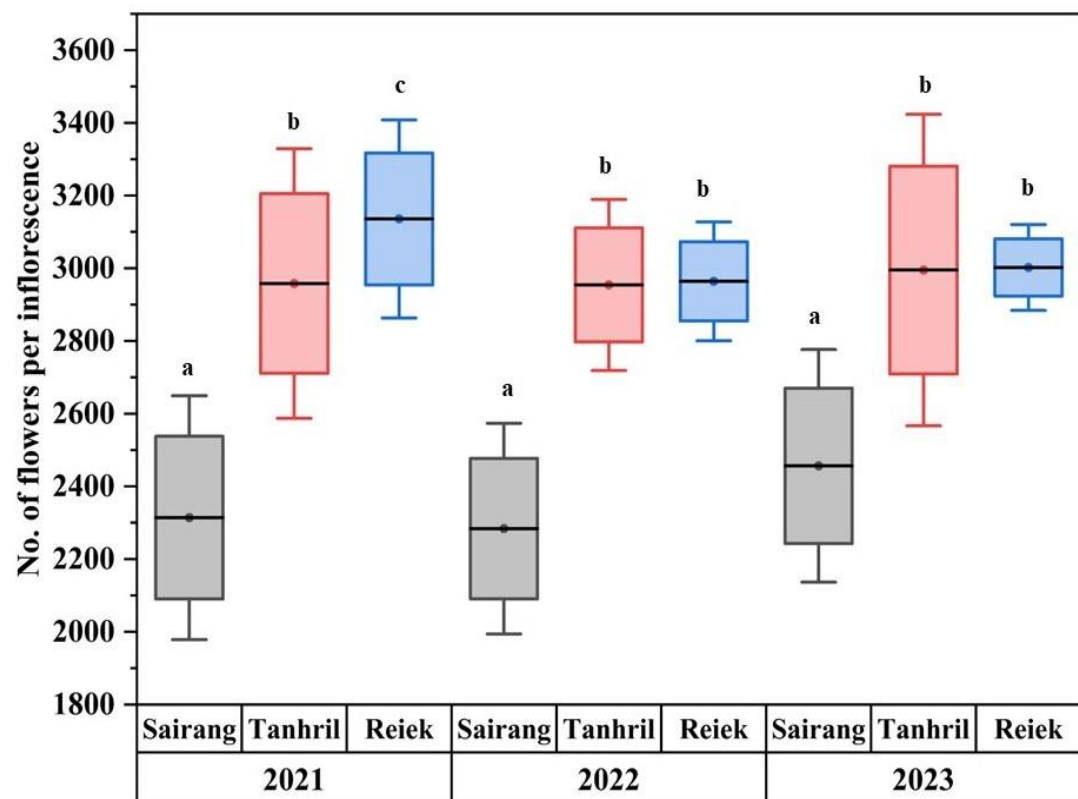


Figure 5.37. No. of flowers per inflorescence for three sites in 2021, 2022 and 2023.

variability. In contrast, Sairang and Reiek, situated at lower and higher altitudes, respectively, exhibited more stable production patterns.

5.7.1.1.2. No. of flowers per inflorescence

The mean number of flowers per inflorescence was assessed across three sites - Sairang, Tanhril, and Reiek over a period of three years (2021–2023). In 2021, Reiek exhibited the highest mean number of flowers per inflorescence, with $3.13 \pm 0.12 \times 10^3$, indicating a relatively high and consistent level of flower production. Tanhril followed with a mean of $2.96 \pm 0.25 \times 10^3$ flowers per inflorescence, while Sairang recorded the lowest mean of $2.31 \pm 0.22 \times 10^3$ flowers, with moderate variability (Figure 5.37.). Statistical analysis revealed a significant difference in flower production between all three sites in 2021 ($p < 0.01$), with Reiek showing significantly higher flower production compared to both Tanhril and Sairang, and Tanhril exhibiting significantly higher flower counts than Sairang. In 2022, slight reductions in flower production were observed across all sites, with Sairang showing a decrease to $2.28 \pm 0.19 \times 10^3$ flowers per inflorescence, Tanhril maintaining a similar level at $2.95 \pm 0.16 \times 10^3$, and Reiek's mean declining slightly to $2.96 \pm 0.11 \times 10^3$ (Figure 5.37.). These minor fluctuations suggest that environmental or ecological conditions may have contributed to small variations in flower production. Statistical analysis for 2022 confirmed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), but no significant difference was found between Tanhril and Reiek, indicating that flower production at these two sites, situated at middle and higher altitudes, respectively, remained relatively similar. In 2023, the mean number of flowers per inflorescence increased at all sites, with Sairang reaching $2.46 \pm 0.21 \times 10^3$, Tanhril at $2.99 \pm 0.29 \times 10^3$, and Reiek showing the highest value at $3.00 \pm 0.08 \times 10^3$ (Figure 5.37.). This increase suggests favorable conditions for floral development in 2023, particularly at Reiek, where flower production remained consistently high with reduced variability. Statistical analysis for 2023 again revealed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), but no significant difference was found between Tanhril and Reiek. Across the three years, Reiek consistently exhibited the highest number of flowers per inflorescence, followed by Tanhril and

Sairang. These data highlight the potential influence of altitude on flower production, with Reiek's higher elevation potentially contributing to more stable and consistent floral output.

5.7.1.1.3. No. of nectar secreting flowers

The mean number of nectar-secreting flowers was evaluated across three distinct sites - Sairang, Tanhril, and Reiek over a three-year period (2021–2023). In 2021, Reiek exhibited the highest mean number of nectar-secreting flowers at 390.07 ± 22.89 , followed by Tanhril at 372.07 ± 49.07 and Sairang at 298.13 ± 17.84 (Figure 5.38.). Statistical analysis revealed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), while no significant difference was observed between Tanhril and Reiek. In 2022, a slight reduction in nectar-secreting flowers was recorded at Sairang (293.93 ± 28.23), while Tanhril (379.00 ± 27.32) and Reiek (382.80 ± 20.23) showed only marginal decreases in production (Figure 5.38.). Statistical analysis for 2022 confirmed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), but no significant difference was found between Tanhril and Reiek. In 2023, nectar secreting flowers production showed a slight increase at all sites, with Sairang reaching 300.80 ± 18.69 , Tanhril at 378.93 ± 20.45 , and Reiek continuing to exhibit the highest mean at 396.00 ± 14.34 (Figure 5.38.). Statistical analysis for 2023 revealed significant differences between all three sites ($p < 0.01$), with Reiek maintaining the highest nectar-secreting flowers production, followed by Tanhril and Sairang. The observed increase in nectar-secreting flowers suggests improvements in environmental conditions that may have facilitated enhanced nectar secreting flowers production, particularly at higher altitudes like Reiek. Overall, Reiek consistently produced the highest number of nectar-secreting flowers across all years, with low variability, indicating a more stable and favorable ecological environment. In contrast, Tanhril exhibited a higher degree of variability, especially in 2021, suggesting that mid-altitude sites may be more susceptible to fluctuations in environmental conditions. Sairang, situated at the lowest altitude, demonstrated the lowest and most stable production of nectar-secreting flowers.

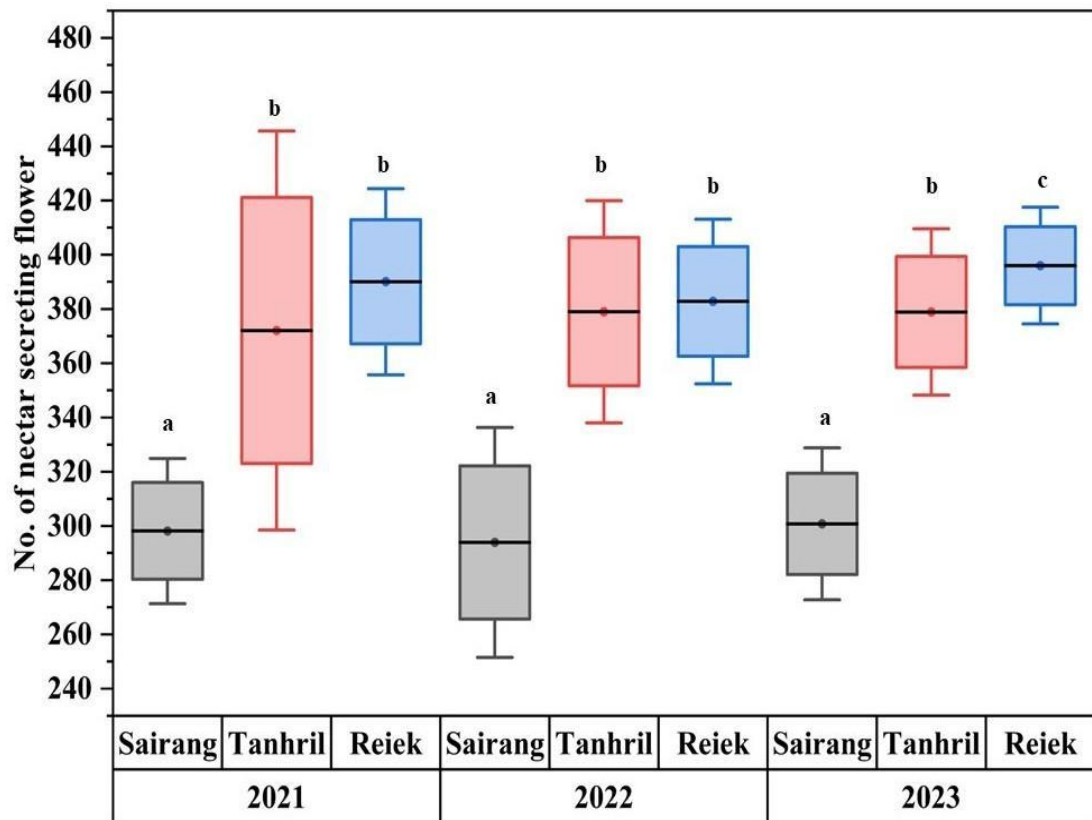


Figure 5.38. No. of nectar secreting flowers for three sites in 2021, 2022 and 2023.

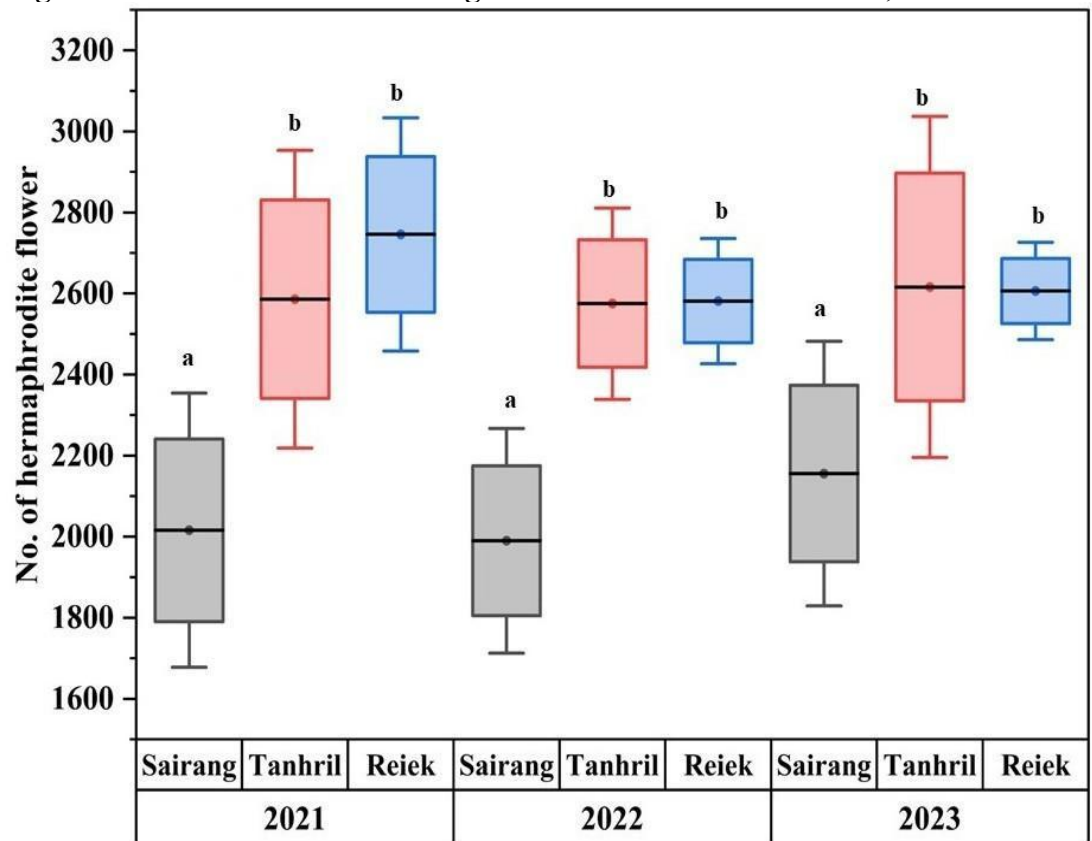


Figure 5.39. No. of hermaphrodite flowers for three sites in 2021, 2022 and 2023.

5.7.1.1.4. No. of hermaphrodite flowers

The number of hermaphrodite flowers was assessed across three sites - Sairang, Tanhril, and Reiek over a period of three years (2021–2023). In 2021, Reiek exhibited the highest mean number of hermaphrodite flowers at $2.74 \pm 0.19 \times 10^3$, followed by Tanhril at $2.59 \pm 0.24 \times 10^3$ and Sairang at $2.01 \pm 0.22 \times 10^3$ (Figure 5.39.). Statistical analysis revealed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), while no significant difference was observed between Tanhril and Reiek. This pattern suggests that the higher altitude of Reiek may contribute to more favorable conditions for hermaphrodite flower production, with lower variability compared to Tanhril, which exhibited greater fluctuation in flower production. In contrast, Sairang, located at the lowest altitude, recorded the lowest mean flower production, though with similar variability to Tanhril, indicating relatively stable but lower reproductive output. In 2022, a slight reduction in flower production was observed across all sites, with Sairang showing a decrease to $1.99 \pm 0.18 \times 10^3$, Tanhril at $2.57 \pm 0.16 \times 10^3$, and Reiek at $2.58 \pm 0.10 \times 10^3$ (Figure 5.39.). Statistical analysis for 2022 confirmed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), but no significant difference was found between Tanhril and Reiek. These modest fluctuations suggest that environmental or ecological factors may have influenced floral output. In 2023, flower production increased slightly at all sites, with Sairang reaching $2.15 \pm 0.22 \times 10^3$, Tanhril at $2.62 \pm 0.28 \times 10^3$, and Reiek maintaining a high mean of $2.61 \pm 0.08 \times 10^3$ (Figure 5.39.). Statistical analysis for 2023 revealed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), but no significant difference was observed between Tanhril and Reiek. The increase in flower production at all sites in 2023 may suggest improved ecological conditions, particularly at Reiek, which continued to exhibit high and stable production. Reiek consistently supported the highest number of hermaphrodite flowers, with the lowest variability, indicating more stable environmental conditions compared to Tanhril and Sairang. Overall, the data suggest that altitudinal differences play a significant role in floral production, with higher altitudes potentially promoting more stable reproductive output, as observed at Reiek. In contrast, Tanhril and Sairang exhibited greater variability, likely due to site-specific ecological factors.

5.7.1.1.5. No. of anthers per flower

The number of anthers per flower was evaluated across three sites - Sairang, Tanhril, and Reiek over the course of three years (2021–2023), and the results demonstrated complete consistency across all sites and years. These sites are located at different altitudes, with Reiek situated at the highest elevation, followed by Tanhril at mid-altitude, and Sairang at the lowest elevation. For each site, the no. of anthers per flower was consistently recorded at 10, with a standard deviation of 0.00, indicating no variation in this trait within each site over the study period (Figure 5.40.). Statistical analysis revealed no significant difference in the no. of anthers between any of the sites for all three years (2021, 2022, and 2023) at the 0.05 significance level. This uniformity in anther number suggests that the trait is genetically fixed and not influenced by the differing altitudes or other environmental factors in the context of this study. The lack of variability across years further supports the idea that the number of anthers per flower is a stable morphological characteristic for the plants at these sites, likely reflecting genetic determination rather than phenotypic plasticity. This consistent floral trait provides valuable insight into the reproductive morphology of the studied species and suggests that certain aspects of floral structure, such as the number of anthers, may be less responsive to environmental fluctuations than other, more variable traits. These findings emphasize the genetic stability of this reproductive feature, highlighting its role as a conserved morphological trait across sites and years, irrespective of the altitudinal variation among the study sites.

5.7.1.1.6. No. of pollen per anther

The data collected on the number of pollen per anther across three different sites - Sairang, Tanhril, and Reiek during the years 2021, 2022, and 2023. In 2021, Reiek exhibited the highest mean pollen count per anther at 48.67 ± 3.62 , followed by Tanhril with 44.93 ± 5.87 , and Sairang with the lowest at 38.00 ± 2.80 (Figure 5.41.). Statistical analysis revealed a significant difference between Sairang and both Tanhril and Reiek ($p < 0.01$), while no significant difference was observed between Tanhril and Reiek. This pattern of higher pollen production at Reiek persisted through 2022, where the

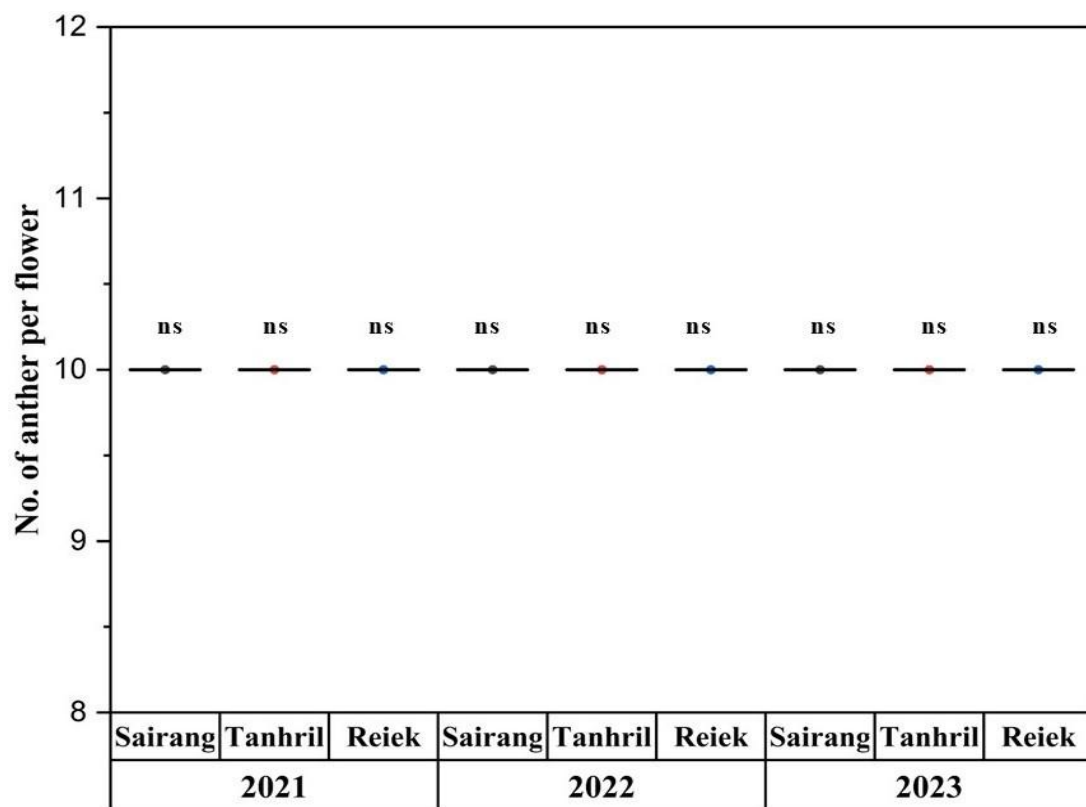


Figure 5.40. No. of anthers per flower for three sites in 2021, 2022 and 2023.

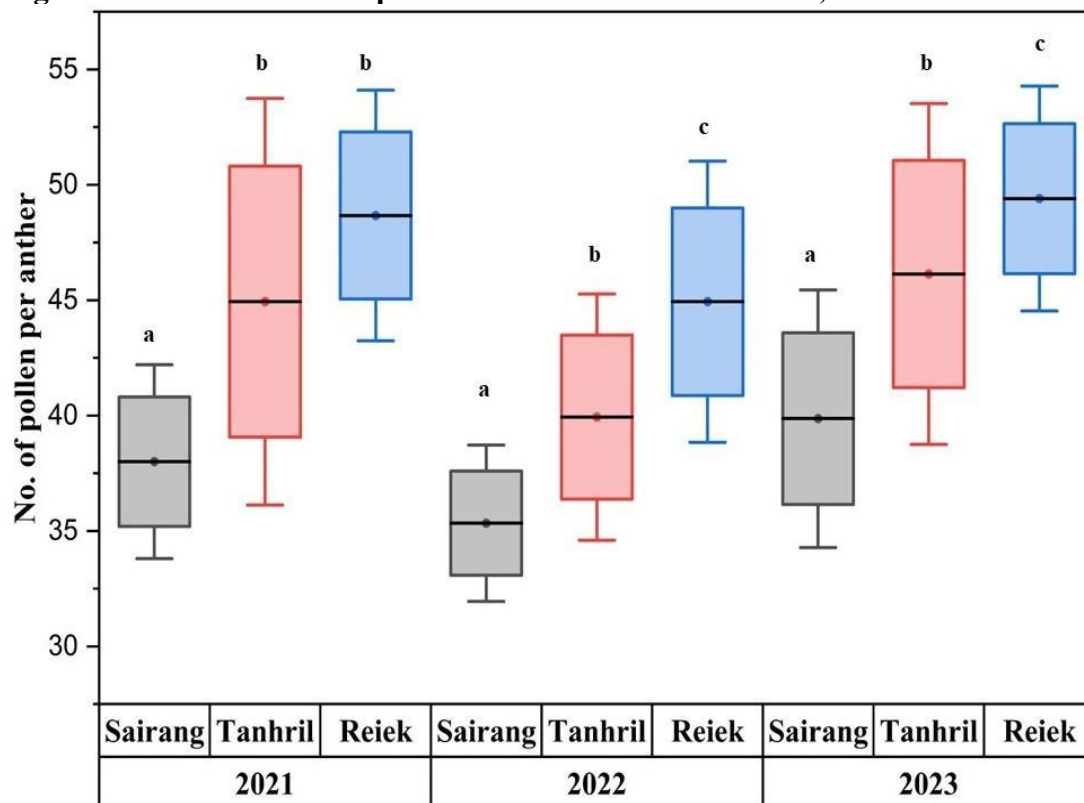


Figure 5.41. No. of pollen per anther for three sites in 2021, 2022 and 2023.

mean at Reiek was 44.93 ± 4.06 , while Tanhril and Sairang exhibited further reductions in pollen production, with values of 39.93 ± 3.56 and 35.33 ± 2.26 , respectively (Figure 5.41.). Statistical analysis for 2022 confirmed significant differences between all three sites ($p < 0.01$), indicating that environmental or ecological factors, affected pollen production across the sites. In 2023, the pollen count per anther increased across all sites, with Sairang showing a mean of 39.87 ± 3.72 , Tanhril at 46.13 ± 4.93 , and Reiek at 49.40 ± 3.25 (Figure 5.41.). Statistical analysis for 2023 revealed significant differences between all three sites ($p < 0.01$), highlighting that the recovery in pollen production was not uniform across the sites, with Reiek continuing to exhibit the highest mean. These observations indicate that, although there was a general decline in pollen production in 2022, particularly at Sairang and Tanhril, a recovery was evident in 2023, especially at Reiek. The temporal variation observed in pollen production underscores the potential influence of environmental factors on the reproductive health of plants across different sites.

5.7.1.1.7. No. of flowers per tree

The temporal and spatial variations in the number of flowers per tree across three study sites -Sairang, Tanhril, and Reiek were assessed over a period of three years, from 2021 to 2023. In 2021, Tanhril exhibited the highest mean number of flowers per tree at $17.45 \pm 2.59 \times 10^5$, followed by Reiek with $12.96 \pm 1.23 \times 10^5$, and Sairang, which produced the lowest count of $10.04 \pm 1.23 \times 10^5$ (Figure 5.42.). Statistical analysis for 2021 revealed significant differences between all three sites ($p < 0.01$). However, by 2022, a noticeable decline in floral production was observed across all sites. The mean number of flowers per tree decreased to $9.63 \pm 1.18 \times 10^5$ in Sairang, $17.06 \pm 1.24 \times 10^5$ in Tanhril, and $13.14 \pm 0.77 \times 10^5$ in Reiek (Figure 5.42.). This reduction may reflect broader environmental or ecological shifts affecting flower production at these sites. Statistical analysis for 2022 confirmed significant differences between all three sites ($p < 0.01$). In 2023, a partial recovery was evident in floral counts, with Sairang showing an increase to $10.94 \pm 1.52 \times 10^5$, Tanhril rising to $17.79 \pm 1.76 \times 10^5$, and Reiek reaching $14.55 \pm 0.81 \times 10^5$ (Figure 5.42.). Statistical analysis for 2023 again revealed significant differences between all three sites ($p < 0.01$). These findings

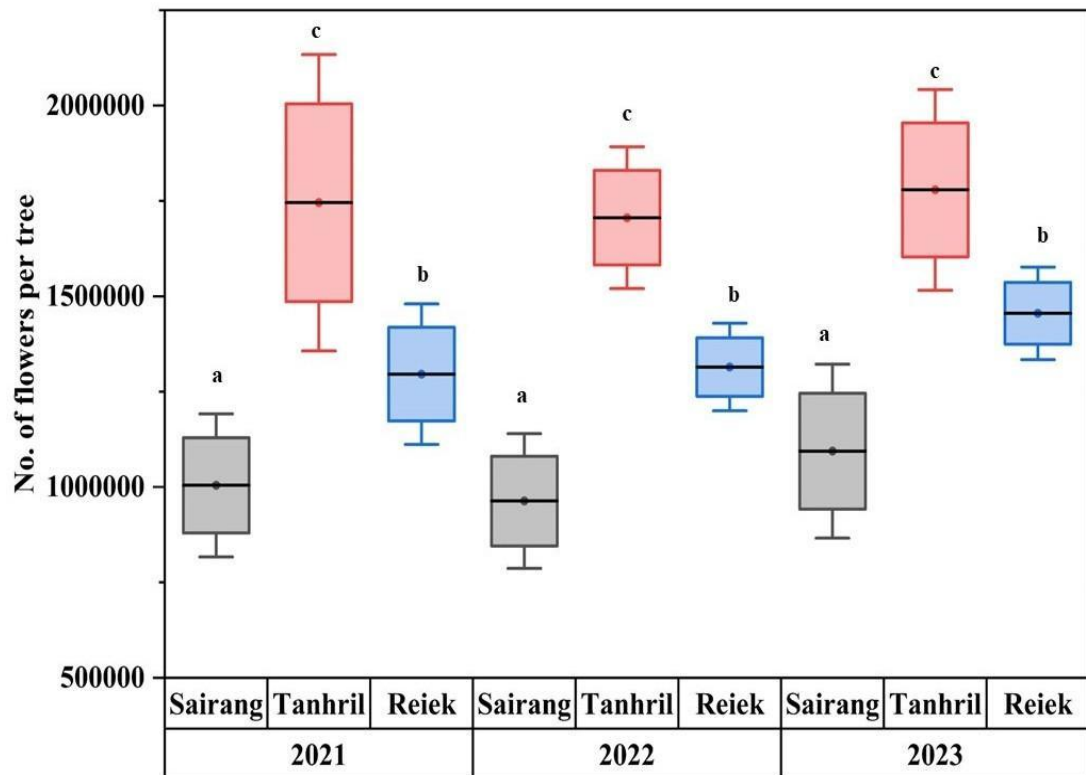


Figure 5.42. No. of flowers per tree for three sites in 2021, 2022 and 2023.

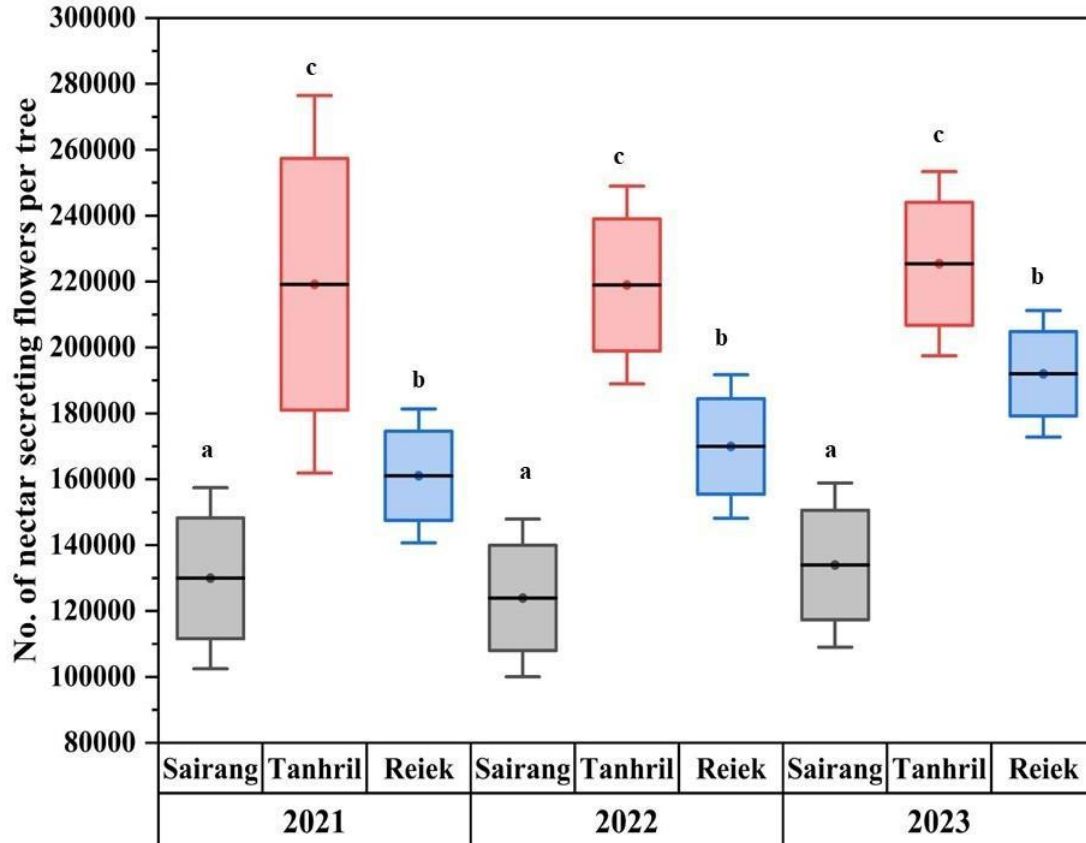


Figure 5.43. No. of nectar secreting flowers per tree for three sites in 2021, 2022 and 2023.

suggest that while floral production declined across all sites in 2022, there was a moderate rebound in 2023, particularly in Tanhril and Reiek. The observed fluctuations in flower production highlight the potential influence of site-specific factors which may contribute to varying reproductive success across sites.

5.7.1.1.8. No. of nectar secreting flowers per tree

The number of nectar-secreting flowers per tree was examined across three sites - Sairang, Tanhril, and Reiek from 2021 to 2023. In 2021, Tanhril exhibited the highest no. of nectar-secreting flowers per tree at $2.19 \pm 0.38 \times 10^5$, followed by Reiek with $1.61 \pm 0.14 \times 10^5$ and Sairang with the lowest at $1.30 \pm 0.18 \times 10^5$ (Figure 5.43.). Statistical analysis for 2021 revealed significant differences between all three sites ($p < 0.01$). In 2022, all sites experienced a decrease in the number of nectar-secreting flowers, with Sairang showing $1.24 \pm 0.16 \times 10^5$, Tanhril at $2.19 \pm 0.20 \times 10^5$, and Reiek at $1.70 \pm 0.15 \times 10^5$ (Figure 5.43.). Statistical analysis for 2022 confirmed significant differences between all three sites ($p < 0.01$), suggesting that environmental stresses may have contributed to the reduced number of nectar-secreting flowers. However, in 2023, there was a recovery in the number of nectar-secreting flowers across all sites. Sairang increased to $1.34 \pm 0.17 \times 10^5$, Tanhril reached $2.25 \pm 0.19 \times 10^5$, and Reiek showed the most significant increase to $1.92 \pm 0.13 \times 10^5$ (Figure 5.43.). Statistical analysis for 2023 also revealed significant differences between all three sites ($p < 0.01$), indicating that the recovery in the number of nectar-secreting flowers across all sites. These findings suggest that environmental factors influencing nectar-secreting flower production might have been alleviated in 2023. The temporal fluctuations observed in the number of nectar-secreting flowers across sites highlight its responsiveness to ecological and environmental conditions.

5.7.1.1.9. No. of hermaphrodite flowers per tree

The number of hermaphrodite flowers per tree was assessed across three distinct sites - Sairang, Tanhril, and Reiek over a three-year period, from 2021 to 2023. In 2021, Tanhril recorded the highest mean number of hermaphrodite flowers per tree, with $15.26 \pm 2.40 \times 10^5$, followed by Reiek at $11.35 \pm 1.17 \times 10^5$ and Sairang with $8.74 \pm 1.14 \times 10^5$ (Figure 5.44.). Statistical analysis for 2021 revealed significant differences

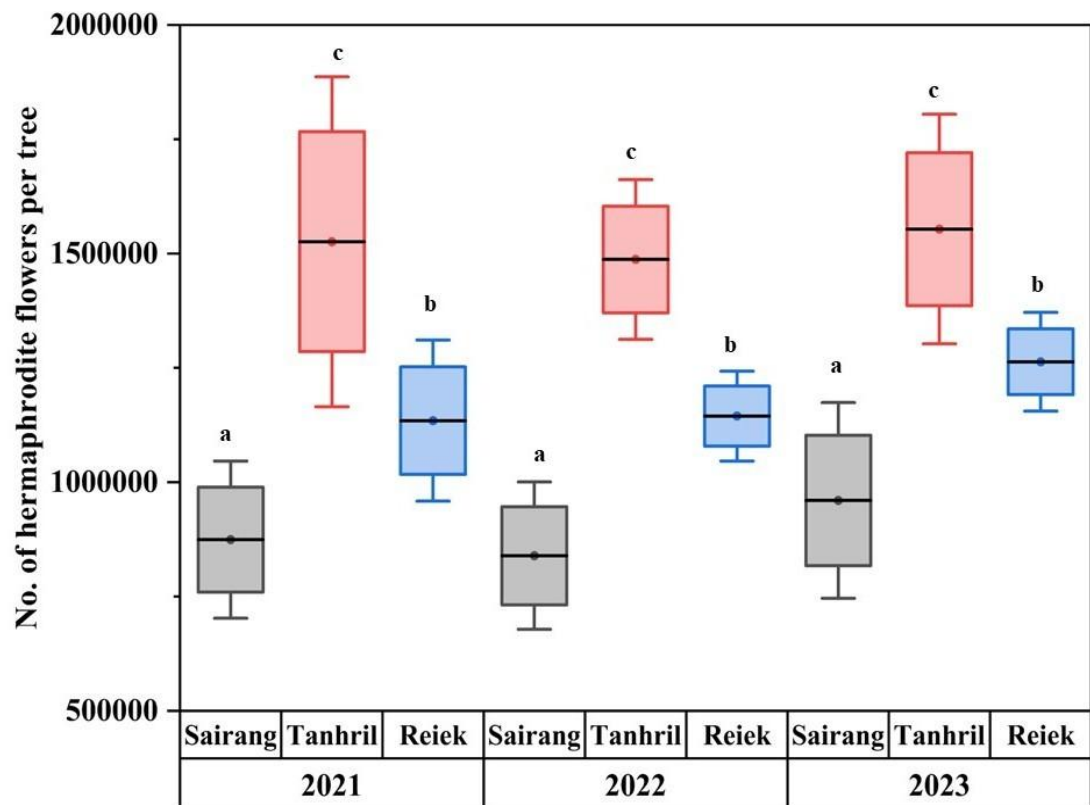


Figure 5.44. No. of hermaphrodite flowers per tree for three sites in 2021, 2022 and 2023.

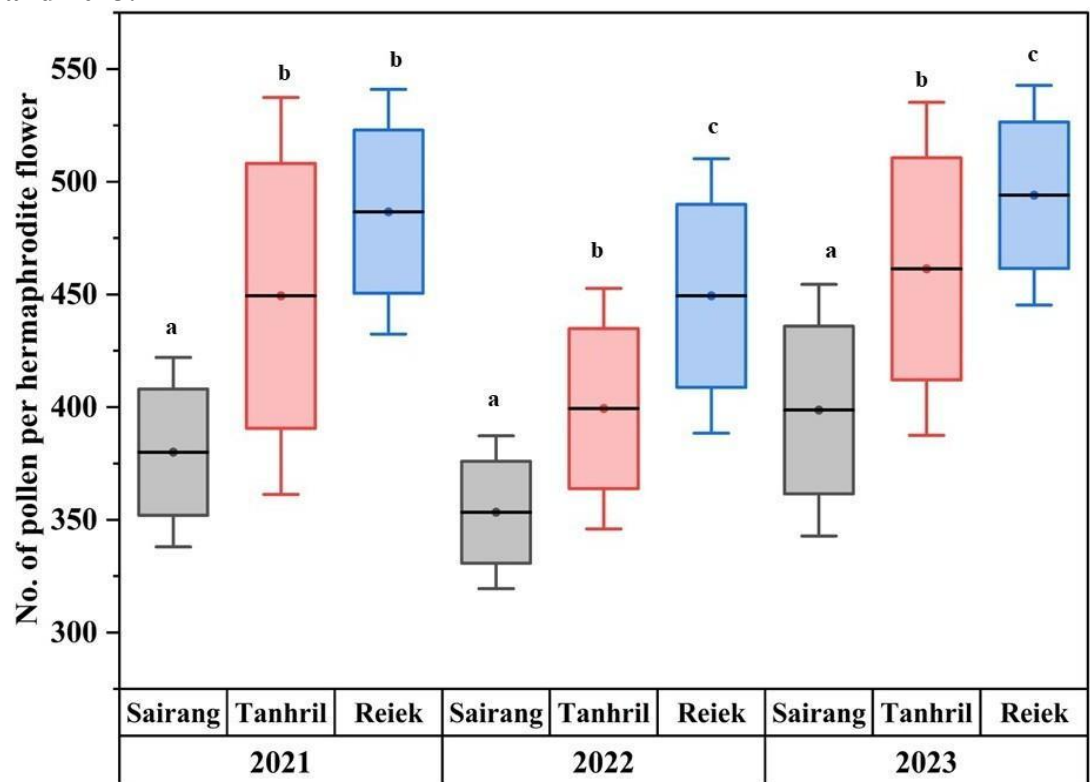


Figure 5.45. No. of pollen per hermaphrodite flower for three sites in 2021, 2022 and 2023.

between all three sites ($p < 0.01$). In 2022, a slight decline in hermaphrodite flower production was observed across all sites, with Sairang showing a decrease to $8.39 \pm 1.07 \times 10^5$, Tanhril at $14.87 \pm 1.16 \times 10^5$, and Reiek slightly dropping to $11.45 \pm 0.66 \times 10^5$ (Figure 5.44.). Statistical analysis for 2022 confirmed significant differences between all three sites ($p < 0.01$), suggesting that environmental factors, such as climate variation or resource limitation, could have influenced reproductive success during this year. However, in 2023, a recovery in flower production was evident across all sites, with Sairang rising to $9.60 \pm 1.43 \times 10^5$, Tanhril reaching $15.53 \pm 1.67 \times 10^5$, and Reiek increasing to $12.63 \pm 0.72 \times 10^5$ (Figure 5.44.). Statistical analysis for 2023 also revealed significant differences between all three sites ($p < 0.01$), indicating that despite the fluctuations in 2022, floral production in 2023 was restored across all sites. These findings suggest that the fluctuations in hermaphrodite flower production are likely influenced by site-specific environmental factors, highlighting the dynamic nature of plant reproduction.

5.7.1.1.10. No. of pollen per hermaphrodite flower

The number of pollen grains per hermaphrodite flower was evaluated across three sites - Sairang, Tanhril, and Reiek over a three-year period, from 2021 to 2023. In 2021, Reiek exhibited the highest pollen count per hermaphrodite flower, with 486.67 ± 36.19 , followed by Tanhril at 449.33 ± 58.73 and Sairang with the lowest count of 380.00 ± 28.03 (Figure 5.45.). Statistical analysis for 2021 revealed a significant difference between Sairang and both Tanhril and Reiek ($p < 0.01$), but no significant difference was observed between Tanhril and Reiek. In 2022, a decline in pollen production was observed across all sites, with Sairang showing a decrease to 353.33 ± 22.57 , Tanhril at 399.33 ± 35.55 , and Reiek at 449.33 ± 40.61 (Figure 5.45.). Statistical analysis for 2022 confirmed significant differences between all three sites ($p < 0.01$), indicating that external environmental stressors or unfavorable ecological conditions may have affected pollen production. Interestingly, in 2023, pollen production rebounded across all sites, with Sairang increasing to 398.67 ± 37.20 , Tanhril rising to 461.33 ± 49.26 , and Reiek maintaining the highest pollen count at 494.00 ± 32.47 (Figure 5.45.). Statistical analysis for 2023 also revealed significant differences

between all three sites ($p < 0.01$), highlighting that the conditions in 2023 facilitated an increase in pollen production, particularly at Reiek and Tanhril. These findings suggest that while the decline in 2022 may have been influenced by external factors, environmental conditions in 2023 supported a recovery in pollen production across all sites. The observed fluctuations in pollen production highlight the complex interplay between environmental factors and reproductive processes.

5.7.1.1.11. No. of pollen per inflorescence

The number of pollen grains per inflorescence was analyzed across three sites - Sairang, Tanhril, and Reiek over a three-year period (2021 to 2023). In 2021, Reiek exhibited the highest mean pollen count per inflorescence, with $13.34 \pm 1.15 \times 10^5$, followed by Tanhril at $11.57 \pm 1.60 \times 10^5$ and Sairang with the lowest count of $7.65 \pm 0.94 \times 10^5$ (Figure 5.46.). Statistical analysis for 2021 revealed significant differences between all three sites ($p < 0.01$). However, in 2022, a decline in pollen production was observed across all sites, with Sairang decreasing to $7.03 \pm 0.85 \times 10^5$, Tanhril at $10.28 \pm 1.10 \times 10^5$, and Reiek at $11.60 \pm 1.18 \times 10^5$ (Figure 5.46.). Statistical analysis for 2022 also confirmed significant differences between all three sites ($p < 0.01$), suggesting that external environmental factors, such as unfavorable weather conditions may have influenced pollen production. By 2023, there was a recovery in pollen production across all three sites, with Sairang increasing to $8.57 \pm 0.99 \times 10^5$, Tanhril rising to $12.06 \pm 1.77 \times 10^5$, and Reiek showing the highest increase to $12.87 \pm 0.83 \times 10^5$ (Figure 5.46.). Statistical analysis for 2023 revealed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), but no significant difference was observed between Tanhril and Reiek. These results suggest that while there was a decline in pollen production in 2022, the environmental conditions in 2023 were more conducive to pollen production, leading to a notable rebound, particularly at Reiek and Tanhril. The fluctuations in pollen production across the three sites highlight the importance of understanding the environmental and ecological factors that influence reproductive success in plants, and further research is needed to explore these underlying drivers.

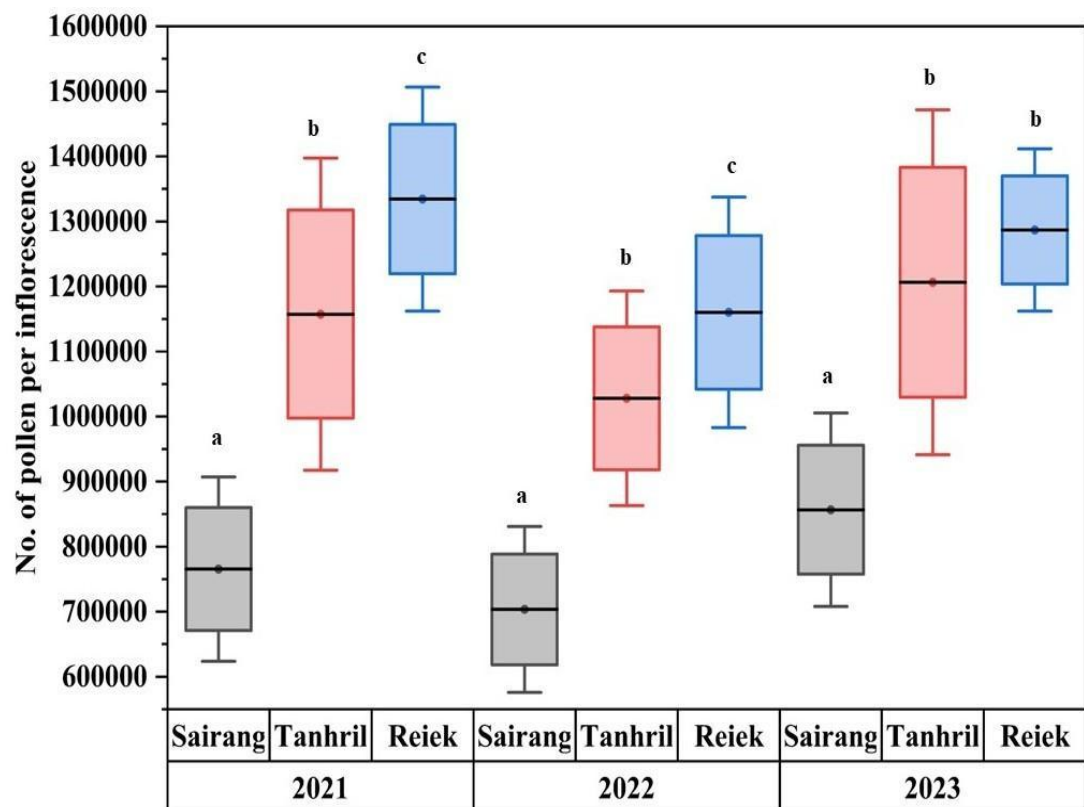


Figure 5.46. No. of pollen per inflorescence for three sites in 2021, 2022 and 2023.

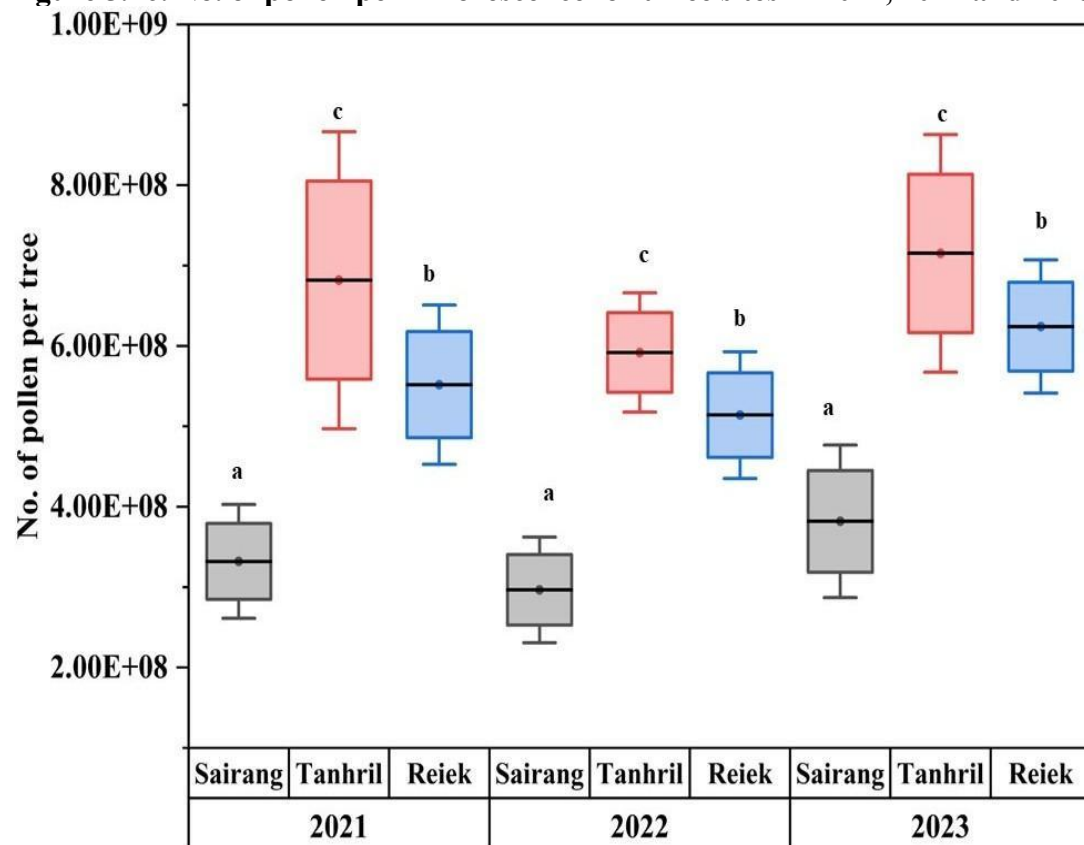


Figure 5.47. No. of pollen per tree for three sites in 2021, 2022 and 2023.

5.7.1.1.12. No. of pollen per tree

The total number of pollen grains per tree was analyzed across three distinct sites - Sairang, Tanhril, and Reiek over a period from 2021 to 2023. In 2021, Tanhril recorded the highest mean pollen count per tree at $6.82 \pm 1.23 \times 10^8$, followed by Reiek at $5.52 \pm 0.66 \times 10^8$ and Sairang at $3.32 \pm 0.47 \times 10^8$ (Figure 5.47.). Statistical analysis for 2021 revealed significant differences between all three sites ($p < 0.01$), with Tanhril exhibiting the highest reproductive output during this year. However, in 2022, a decline in pollen production was observed at all three sites, with Sairang decreasing to $2.97 \pm 0.44 \times 10^8$, Tanhril at $5.92 \pm 0.49 \times 10^8$, and Reiek at $5.14 \pm 0.53 \times 10^8$ (Figure 5.47.). The reduction in pollen production across these sites in 2022 can be attributed to various ecological and environmental factors, including climatic variation and potential disruptions to plant reproductive cycles. Statistical analysis for 2022 confirmed significant differences between all three sites ($p < 0.01$), suggesting that environmental stressors may have influenced reproductive success. In 2023, however, there was a marked recovery in pollen production across all three sites, with Sairang increasing to $3.82 \pm 0.63 \times 10^8$, Tanhril showing a substantial rise to $7.15 \pm 0.98 \times 10^8$, and Reiek increasing to $6.24 \pm 0.55 \times 10^8$ (Figure 5.47.). Statistical analysis for 2023 again revealed significant differences between all three sites ($p < 0.01$), indicating that environmental conditions in 2023 were more conducive to pollen production, leading to an overall increase in reproductive output, especially at Tanhril. These findings suggest that fluctuations in pollen production across the years indicate that environmental factors significantly influence the reproductive success of plants.

5.7.1.1.13. No. of ovules per flower

The number of ovules per flower was evaluated across three sites - Sairang, Tanhril, and Reiek over a three-year period (2021 to 2023). In 2021, Reiek exhibited the highest no. of ovules per flower, with 17.47 ± 2.39 , followed by Tanhril at 16.73 ± 2.40 and Sairang with the lowest count of 14.47 ± 1.60 (Figure 5.48.). Statistical analysis for 2021 revealed significant differences between Sairang and both Tanhril and Reiek ($p < 0.01$), but no significant difference was observed between Tanhril and Reiek. In 2022, there was a slight decrease in ovule production at all sites, with Sairang showing

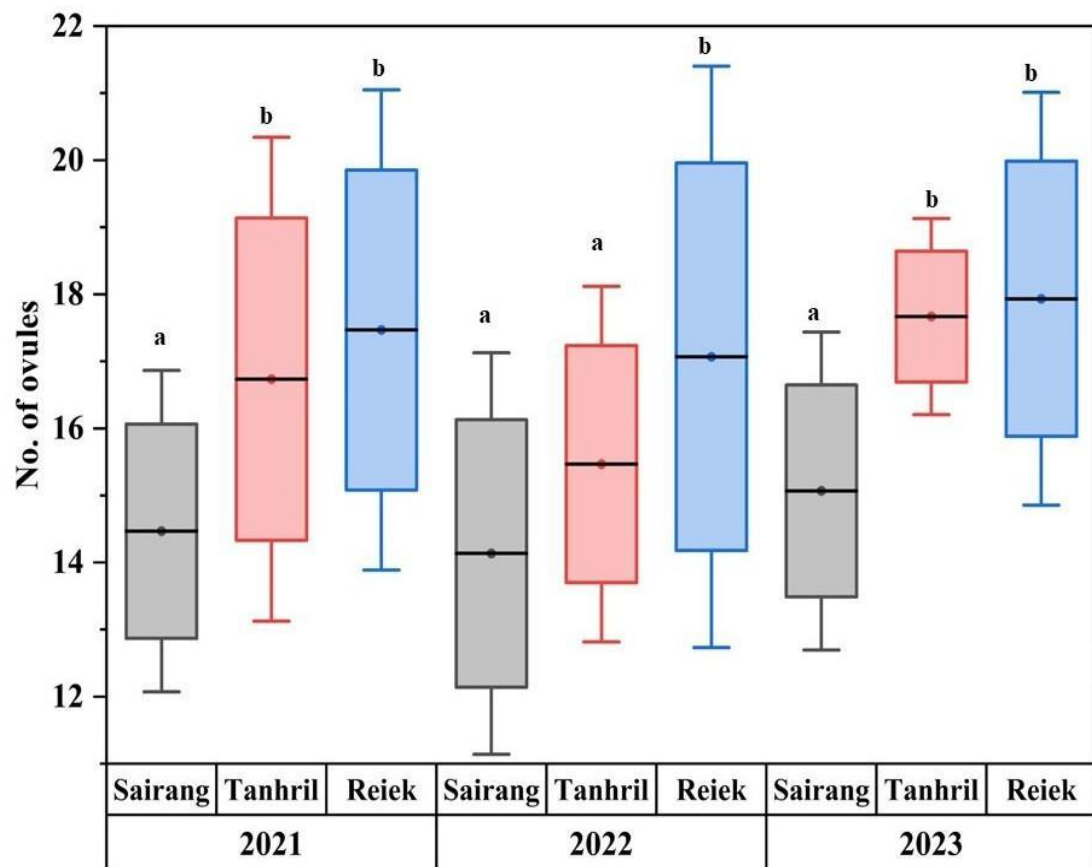


Figure 5.48. No. of ovules per flower for three sites in 2021, 2022 and 2023.

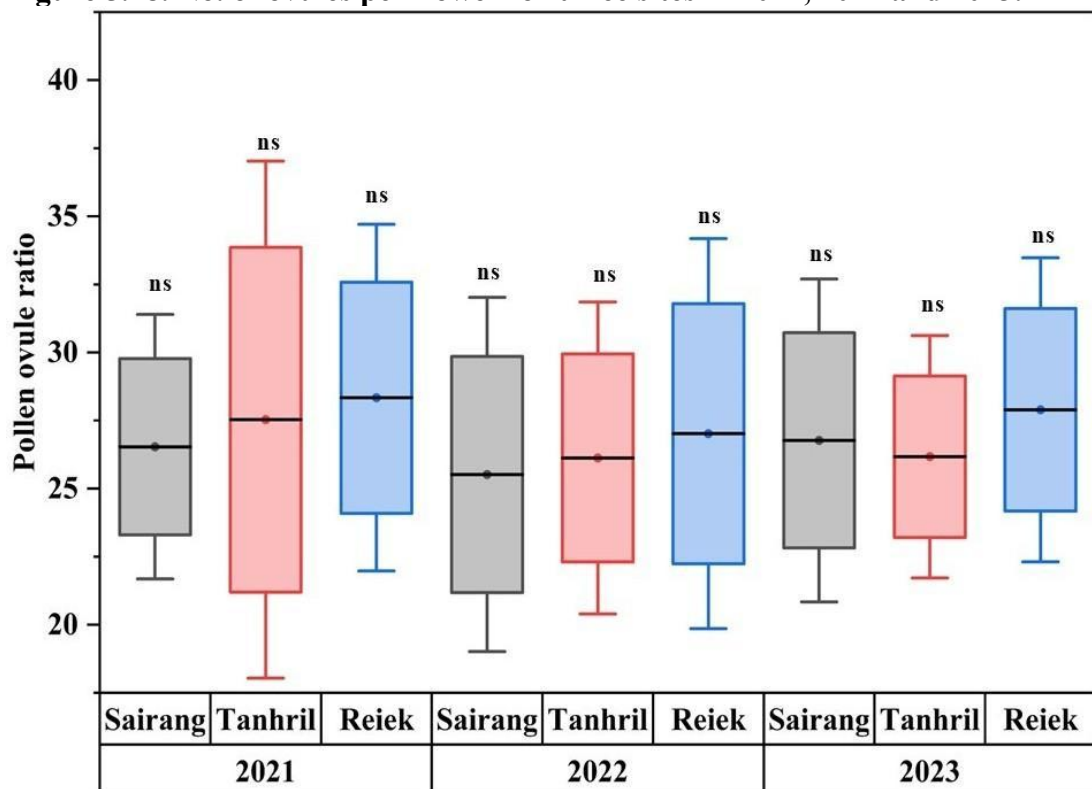


Figure 5.49. Pollen ovule ratio for three sites in 2021, 2022 and 2023.

14.13 $\pm$ 2.00, Tanhril at 15.47 $\pm$ 1.77, and Reiek at 17.07 $\pm$ 2.89 (Figure 5.48.). Statistical analysis for 2022 confirmed a significant difference between Reiek and both Tanhril and Sairang ($p < 0.01$), but no significant difference was found between Tanhril and Sairang, confirming that the decline in ovule production may have been more pronounced at Sairang relative to the other sites. This reduction could be indicative of environmental stressors or other ecological factors that may have impacted reproductive processes. However, in 2023, the ovule count increased across all sites, with Sairang rising to 15.07 $\pm$ 1.58, Tanhril reaching 17.67 $\pm$ 0.98, and Reiek showing the highest increase at 17.93 $\pm$ 2.05 (Figure 5.48.). Statistical analysis for 2023 again revealed significant differences between Sairang and both Tanhril and Reiek but not between Tanhril and Reiek ($p < 0.01$). These findings suggest that while there was a slight decline in ovule production in 2022, environmental conditions in 2023 supported a recovery in reproductive output across the sites, with the most pronounced increase at Reiek and Tanhril.

5.7.1.1.14. Pollen ovule ratio

The pollen to ovule (P/O) ratio was assessed across three sites - Sairang, Tanhril, and Reiek over a three-year period from 2021 to 2023, offering important insights into the reproductive dynamics of the studied plant. In 2021, Reiek exhibited the highest mean P/O ratio at 28.34 $\pm$ 4.25, followed by Tanhril with 27.53 $\pm$ 6.33, and Sairang with the lowest at 26.54 $\pm$ 3.24 (Figure 5.49.). Statistical analysis for 2021 revealed no significant difference between the sites ($p > 0.05$), suggesting that the P/O ratios were comparable across the sites despite slight differences in their reproductive output. In 2022, a slight decrease in the P/O ratio was observed across all sites, with Sairang reducing to 25.52 $\pm$ 4.34, Tanhril to 26.12 $\pm$ 3.82, and Reiek to 27.02 $\pm$ 4.77 (Figure 5.49.). Statistical analysis for 2022 confirmed no significant difference between the sites ($p > 0.05$), indicating that the decline in the P/O ratio was consistent across all sites. This decrease may reflect potential environmental stresses or shifts in pollination efficiency, which could have impacted reproductive success at these sites. Nevertheless, in 2023, the P/O ratio showed a recovery, with Sairang increasing to 26.77 $\pm$ 3.95, Tanhril remaining relatively stable at 26.17 $\pm$ 2.97, and Reiek rising to

27.89 ± 3.72 (Figure 5.49.). Statistical analysis for 2023 again revealed no significant difference between the sites ($p > 0.01$), suggesting that the recovery in reproductive efficiency was similar across the three sites. These findings highlight the importance of environmental conditions in regulating reproductive parameters.

5.7.1.2. Effect of years on pollen production and pollen ovule ratio

5.7.1.2.1. No. of inflorescences per tree

The data presented in the study reflect the number of inflorescences per tree across three distinct sites - Sairang, Tanhril, and Reiek over a three-year period (2021-2023). In Sairang, the number of inflorescences per tree showed slight variation, with values of 435.07 ± 46.66 in 2021, 421.00 ± 26.90 in 2022, and 445.13 ± 44.85 in 2023 (Figure 5.50.). Statistical analysis revealed no significant difference between the years at the 0.01 significance level, indicating that the production of inflorescences remained relatively stable throughout the study period. A similar pattern was observed in Tanhril, where the number of inflorescences per tree was 591.13 ± 83.97 in 2021, 578.00 ± 37.40 in 2022, and 595.00 ± 39.95 in 2023 (Figure 5.50.). Again, no significant difference was found across the years at the 0.05 level, suggesting consistent reproductive output over time in this region. In contrast, Reiek demonstrated a significant increase in the number of inflorescences per tree. The means were 412.93 ± 26.85 in 2021, 443.80 ± 26.32 in 2022, and 485.07 ± 29.55 in 2023 (Figure 5.50.). Statistical analysis revealed a significant difference at the 0.01 level, indicating a clear upward trend in inflorescence production over the three years. These results highlight region-specific patterns in the reproductive biology of the species, with Sairang and Tanhril exhibiting stable trends and Reiek showing significant growth.

5.7.1.2.2. No. of flowers per inflorescence

The data presented here examine the mean number of flowers per inflorescence across three distinct locations - Sairang, Tanhril, and Reiek over a period from 2021 to 2023. In Sairang, the number of flowers per inflorescence was $2.31 \pm 0.22 \times 10^3$ in 2021, $2.28 \pm 0.19 \times 10^3$ in 2022, and $2.46 \pm 0.21 \times 10^3$ in 2023 (Figure 5.51.). Statistical analysis indicates that there was no significant difference between the years at the 0.05

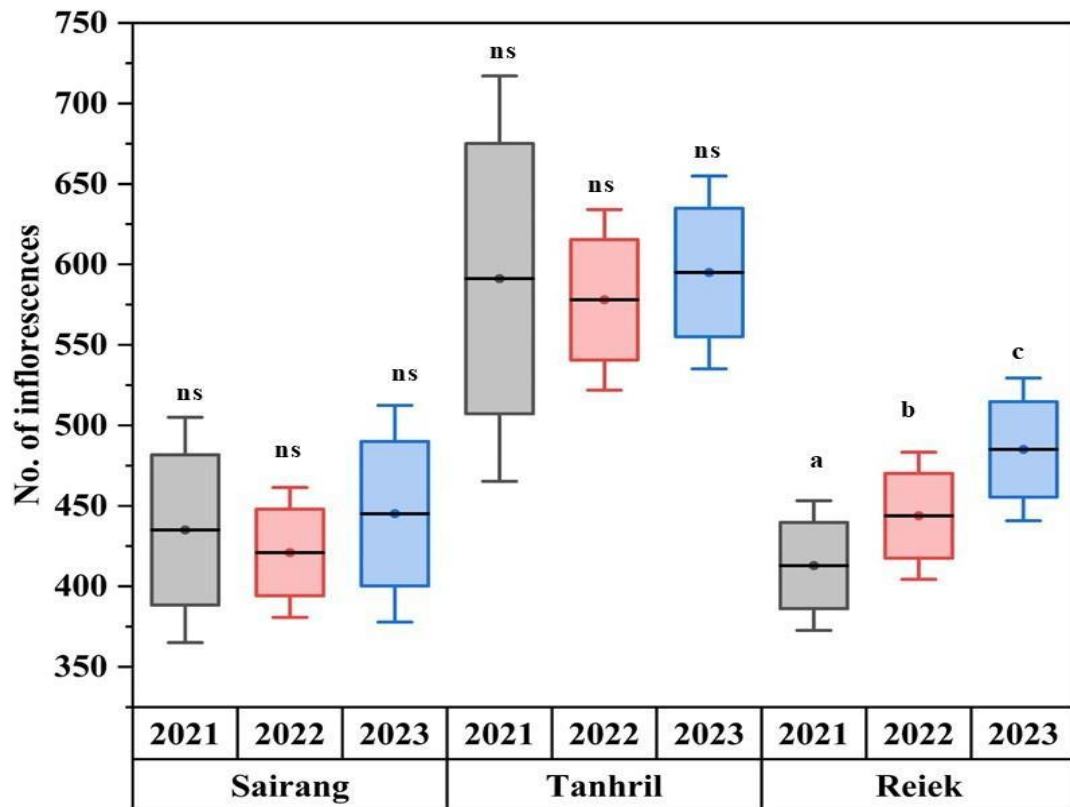


Figure 5.50. No. of inflorescences per tree for three years in Sairang, Tanhril and Reiek.

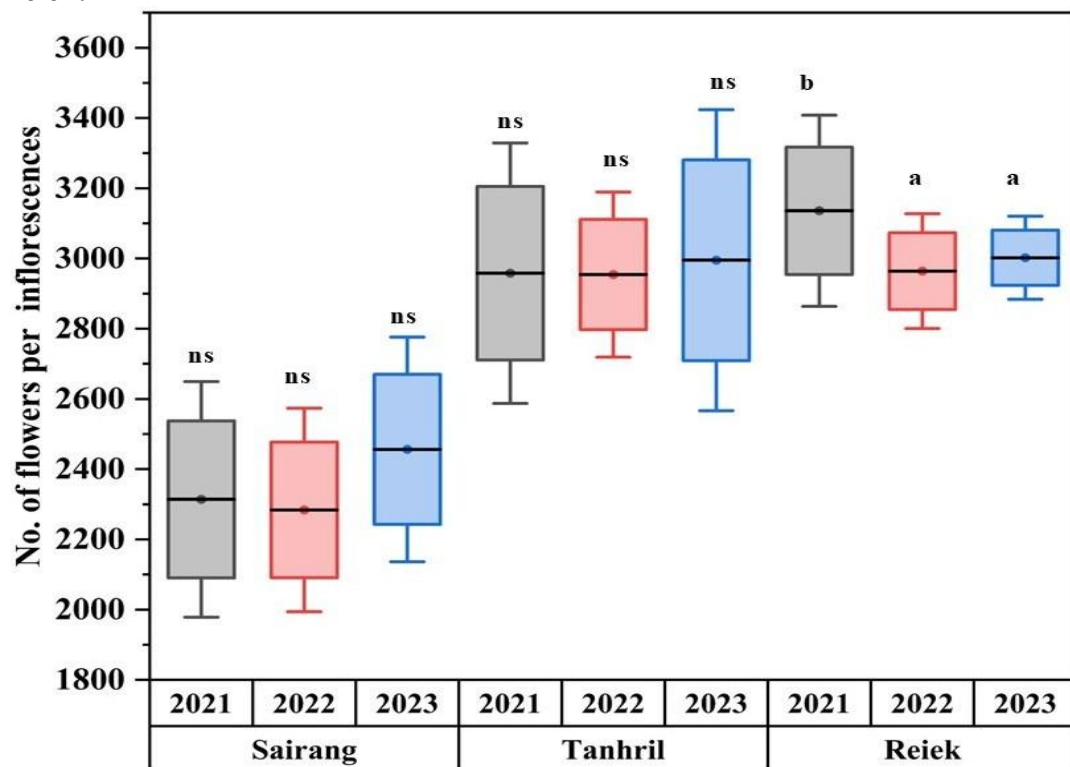


Figure 5.51. No. of flowers per inflorescence for three years in Sairang, Tanhril and Reiek.

significance level, suggesting a relatively stable trend in flower production per inflorescence throughout the study period. A similar pattern was observed in Tanhril, where the number of flowers per inflorescence was $2.96 \pm 0.25 \times 10^3$ in 2021, $2.95 \pm 0.16 \times 10^3$ in 2022, and $2.99 \pm 0.29 \times 10^3$ in 2023 (Figure 5.51.). Again, no significant differences were observed across the years at the 0.05 significance level, indicating consistent flower production across the three years in this location. However, in Reiek, a different trend was observed. The no. of flowers per inflorescence was $3.14 \pm 0.18 \times 10^3$ in 2021, $2.96 \pm 0.11 \times 10^3$ in 2022, and $3.00 \pm 0.08 \times 10^3$ in 2023 (Figure 5.51.). Statistical analysis revealed significant differences between 2021 and both 2022 and 2023 at the 0.01 level, highlighting a notable decrease in flower production in the first year. However, no significant difference was observed between 2022 and 2023, suggesting that flower production in these two years remained comparable. These findings indicate that while flower production per inflorescence remained stable in Sairang and Tanhril, there was a significant decrease in Reiek between 2021 and the following years, though no further significant changes occurred thereafter. The results underscore the potential influence of location-specific environmental factors on flower production dynamics.

5.7.1.2.3. No. of nectar secreting flowers

The study examined the temporal variation in the number of nectar-secreting flowers across three sites - Sairang, Tanhril, and Reiek over a three-year period (2021–2023). The results revealed that in Sairang, the mean number of nectar-secreting flowers showed minimal fluctuation, with values of 298.13 in 2021, 293.93 in 2022, and 300.80 in 2023 (Figure 5.52.). Despite these small changes, the standard deviations were relatively high in 2022 (28.23) but reduced in 2023 (18.69), indicating some degree of variability. Similarly, in Tanhril, the mean values remained stable over the three years: 372.07 in 2021, 379.00 in 2022, and 378.93 in 2023, accompanied by a reduction in standard deviation from 49.07 in 2021 to 20.45 in 2023 (Figure 5.52.). The trend in Reiek was comparable, with the mean number of nectar-secreting flowers recorded at 390.07 in 2021, 382.80 in 2022, and 396.00 in 2023 (Figure 5.52.). The data for Reiek showed a gradual increase in the mean, accompanied by a decrease in standard deviation, from 22.89 in 2021 to 14.34 in 2023. However, statistical analysis

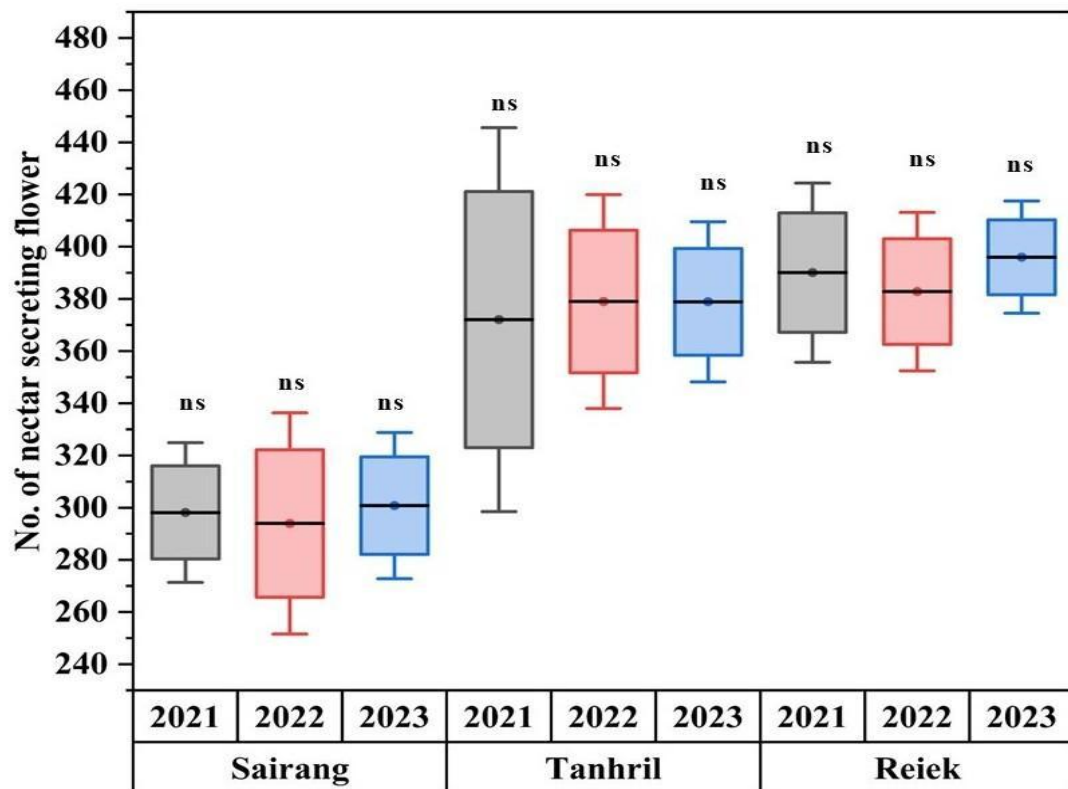


Figure 5.52. No. of nectar secreting flowers for three years in Sairang, Tanhril and Reiek.

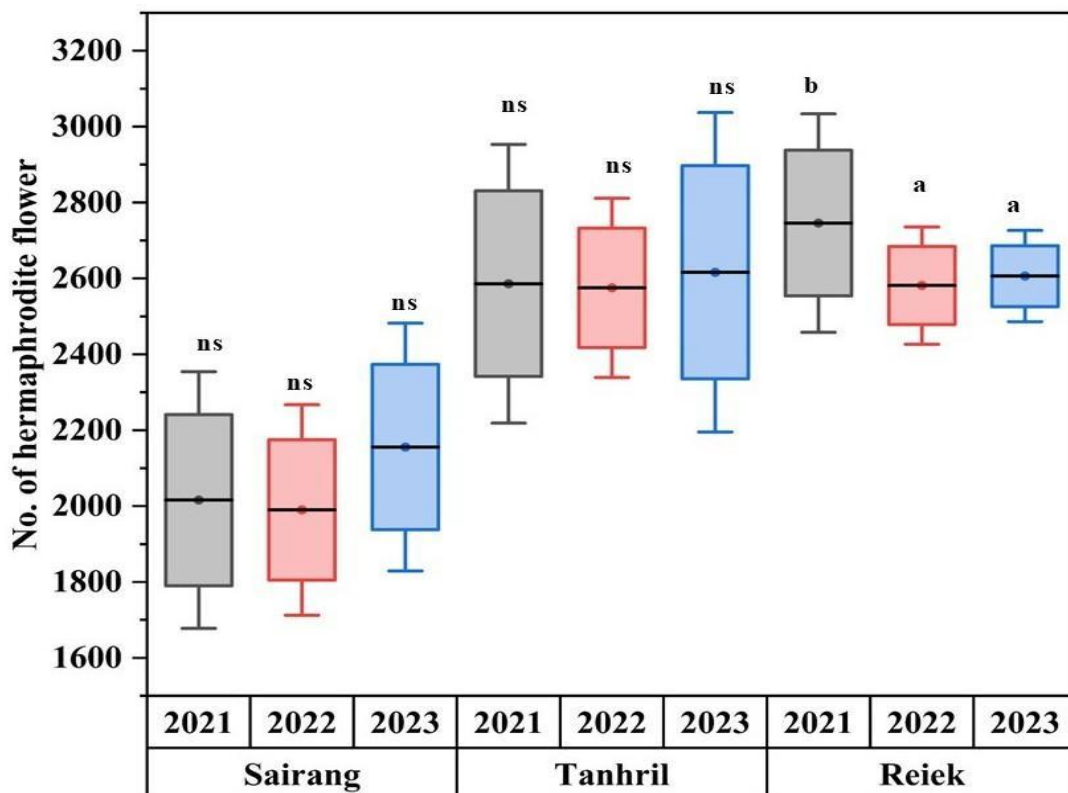


Figure 5.53. No. of hermaphrodite flowers for three years in Sairang, Tanhril and Reiek.

across all three sites indicated no significant differences in the number of nectar-secreting flowers between the years at the 0.05 significance level, suggesting that the observed fluctuations were not statistically meaningful. These findings imply that environmental factors influencing nectar secreting flowers production remained relatively stable over the three-year period. Therefore, the lack of significant variation in flower counts across the sites supports the hypothesis of temporal stability in nectar-secreting flower abundance, despite minor yearly variations.

5.7.1.2.4. No. of hermaphrodite flowers

The analysis of hermaphrodite flower abundance across three sites - Sairang, Tanhril, and Reiek over three years (2021–2023) revealed notable patterns in temporal flower production. In Sairang, the mean number of hermaphrodite flowers showed a gradual decline from $2.01 \pm 0.22 \times 10^3$ in 2021 to $1.99 \pm 0.18 \times 10^3$ in 2022, followed by an increase to $2.15 \pm 0.22 \times 10^3$ in 2023 (Figure 5.53.). Despite these fluctuations, statistical testing indicated that there were no significant differences in flower abundance across the three years at the 0.05 significance level, suggesting that the observed variations were not substantial enough to be considered statistically significant. Similarly, in Tanhril, the number of hermaphrodite flowers remained relatively stable, with mean values of $2.59 \pm 0.24 \times 10^3$ in 2021, $2.58 \pm 0.16 \times 10^3$ in 2022, and $2.62 \pm 0.28 \times 10^3$ in 2023 (Figure 5.53.). Although minor changes were observed, the statistical analysis revealed no significant differences between the years at the 0.05 significance level, confirming the stability of flower production at this site. In contrast, Reiek exhibited more pronounced changes. The mean number of hermaphrodite flowers decreased significantly from $2.74 \pm 0.19 \times 10^3$ in 2021 to $2.58 \pm 0.10 \times 10^3$ in 2022 but showed a slight recovery to $2.61 \pm 0.08 \times 10^3$ in 2023 (Figure 5.53.). Statistical comparisons revealed a significant difference between 2021 and both 2022 and 2023, indicating that the year-to-year changes in flower numbers were statistically significant. However, no significant difference was found between 2022 and 2023, suggesting that after the decrease in 2022, flower numbers in Reiek stabilized in the subsequent year. These findings highlight the complex dynamics of flower production across different sites, with Sairang and Tanhril showing temporal

stability in flower abundance, while Reiek exhibited significant changes between 2021 and the following years.

5.7.1.2.5. No. of anthers per flower

The analysis of the number of anthers per flower across three sites - Sairang, Tanhril, and Reiek over the period from 2021 to 2023 reveals a complete consistency in flower morphology. For each site, the mean number of anthers remained constant at 10.00 throughout the three years, with a standard deviation of 0.00, indicating no variation in the data. In Sairang, Tanhril, and Reiek, the number of anthers per flower was uniform across the years, with no discernible differences observed (Figure 5.54.). Statistical tests confirmed that there was no significant difference in the no. of anthers per flower between the years at the 0.05 significance level. This lack of variation suggests a stable pattern of anther production across the three sites, with no temporal fluctuations or environmental influences affecting flower morphology over the observed period. The absence of variability in the number of anthers per flower emphasizes the reliability of the observed data, indicating that flower structure remained consistent, potentially due to stable ecological or genetic factors influencing floral development.

5.7.1.2.6. No. of pollen per anther

The analysis of pollen production per anther across three sites - Sairang, Tanhril, and Reiek over the years 2021 to 2023 reveals significant temporal variations in pollen grain abundance. In Sairang, the no. of pollen grains per anther showed a decrease from 38.00 ± 2.80 in 2021 to 35.33 ± 2.26 in 2022, followed by an increase to 39.87 ± 3.72 in 2023 (Figure 5.55.). Statistical tests indicated a significant difference between 2022 and both 2021 and 2023, but no significant difference was found between 2021 and 2023, suggesting that the reduction observed in 2022 was temporary and pollen production returned to levels similar to 2021 by the final year of observation. Similarly, in Tanhril, the mean pollen count decreased from 44.93 ± 5.87 in 2021 to 39.93 ± 3.56 in 2022 but increased again to 46.13 ± 4.93 in 2023 (Figure 5.55.). Again, significant differences were observed between 2022 and both 2021 and 2023, while no

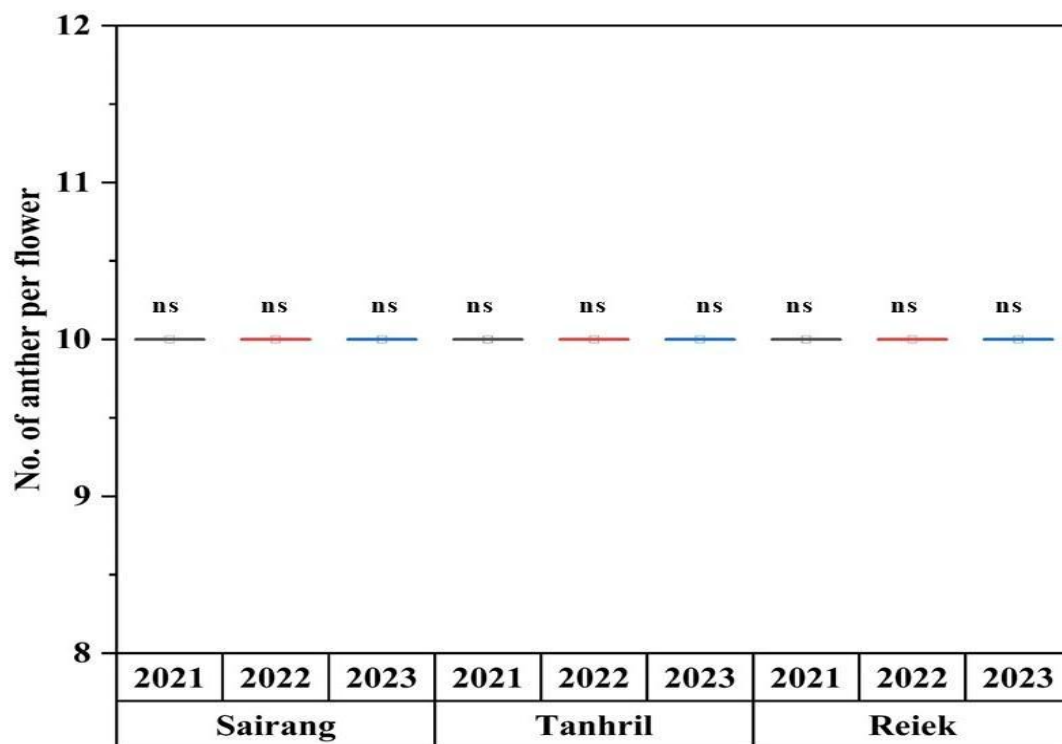


Figure 5.54. No. of anther per flower for three years in Sairang, Tanhril and Reiek.

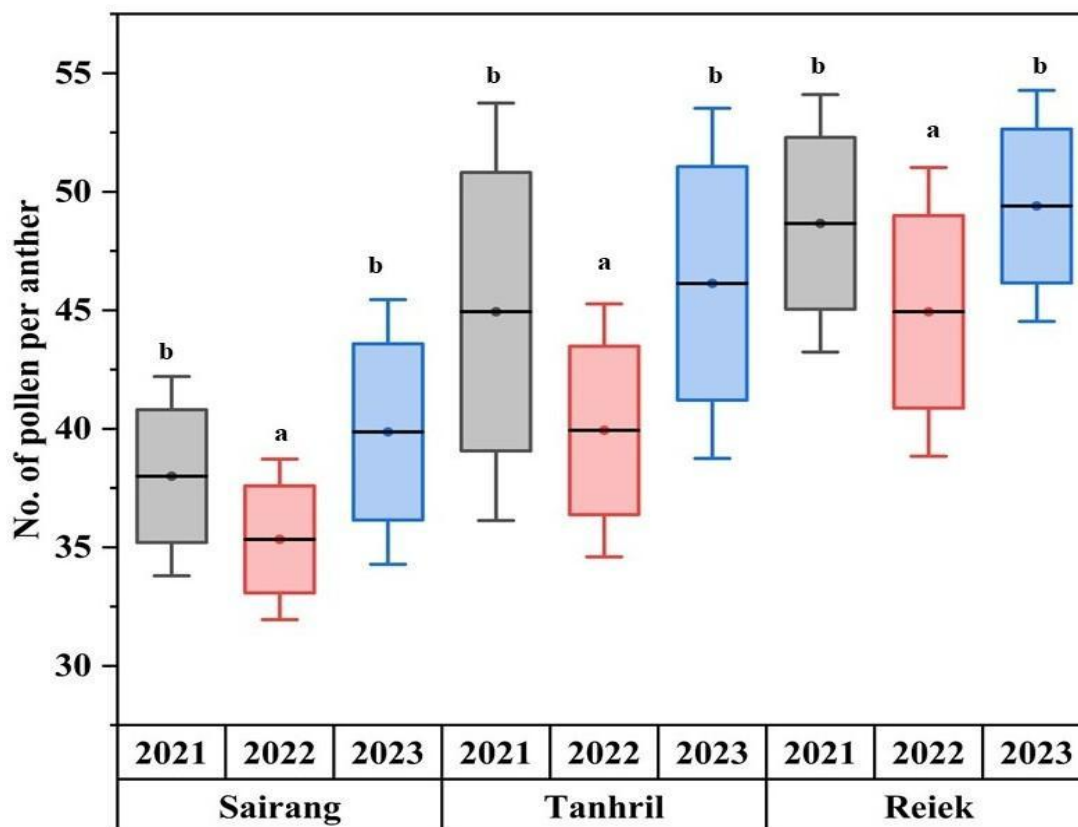


Figure 5.55. No. of pollen per anther for three years in Sairang, Tanhril and Reiek.

significant difference was found between 2021 and 2023, indicating a recovery in pollen production by 2023. In Reiek, the no. of pollen grains per anther followed a similar pattern, with a decrease from 48.67 ± 3.62 in 2021 to 44.93 ± 4.06 in 2022, and a subsequent increase to 49.40 ± 3.25 in 2023 (Figure 5.55.). The statistical analysis confirmed significant differences between 2022 and both 2021 and 2023, but no significant difference was found between 2021 and 2023, suggesting a return to the higher pollen levels observed in 2021 by 2023. Overall, these results indicate that while there were significant fluctuations in pollen production, particularly in 2022, the levels in 2021 and 2023 were statistically similar across all sites. These findings highlight the dynamic nature of pollen production and underscore the need for further investigations into the environmental and ecological factors that may drive such variations over time.

5.7.2.7. No. of flowers per tree

The analysis of total flower production per tree across three sites - Sairang, Tanhril, and Reiek over the period from 2021 to 2023 reveals notable differences in flower abundance and temporal trends. In Sairang, the mean number of total flowers per tree decreased from $10.04 \pm 1.25 \times 10^5$ in 2021 to 9.63 ± 1.18 in 2022, followed by an increase to $10.94 \pm 1.52 \times 10^5$ in 2023 (Figure 5.56.). Statistical comparisons revealed no significant differences between 2021 and both 2022 and 2023; however, a significant difference was observed between 2022 and 2023 at the 0.01 significance level, indicating a significant recovery in flower production in 2023 after a dip in 2022. In Tanhril, the number of flowers per tree remained relatively stable, with values of $17.45 \pm 2.59 \times 10^5$ in 2021, $17.06 \pm 1.24 \times 10^5$ in 2022, and $17.79 \pm 1.76 \times 10^5$ in 2023 (Figure 5.56.). Despite slight fluctuations in the data, statistical analysis confirmed no significant differences between the years, suggesting that flower production remained consistently high across the observed period. In Reiek, the total number of flowers per tree increased from $12.96 \pm 1.23 \times 10^5$ in 2021 to $13.14 \pm 0.77 \times 10^5$ in 2022 and further increased to $14.55 \pm 0.81 \times 10^5$ in 2023 (Figure 5.56.). Significant differences were found between 2023 and both 2021 and 2022, indicating a positive trend in flower production in the latter years of the study. However, no

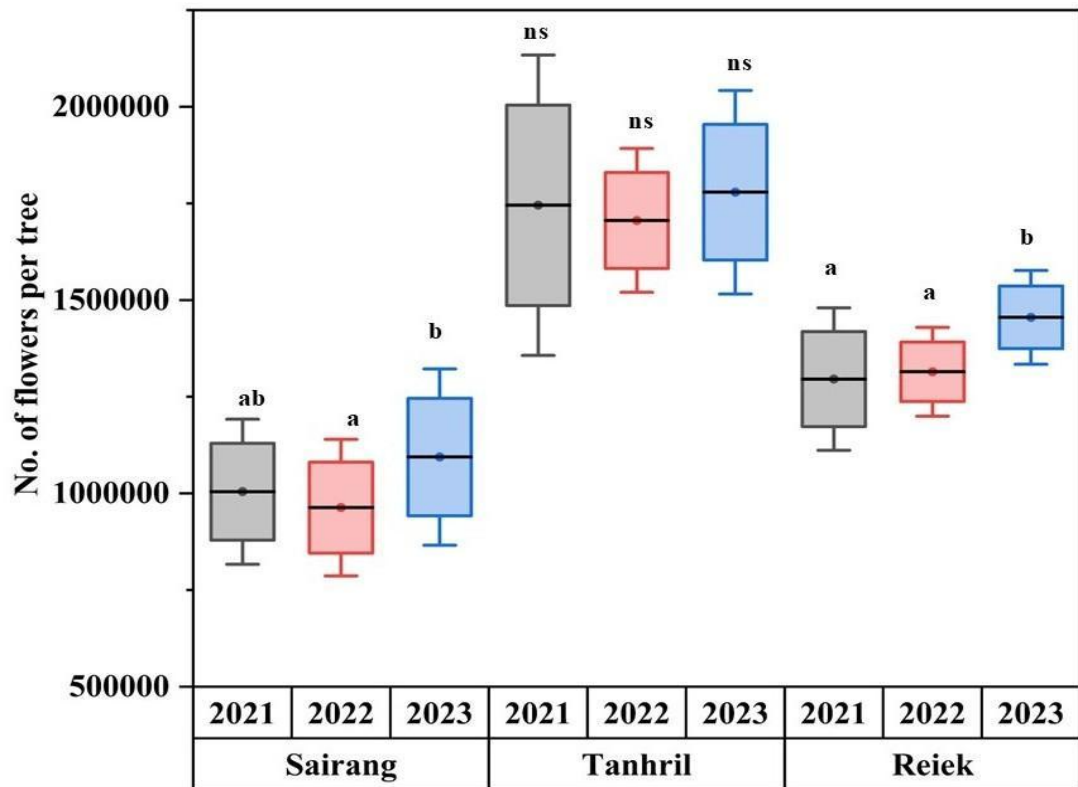


Figure 5.56. No. of flowers per tree for three years in Sairang, Tanhril and Reiek.

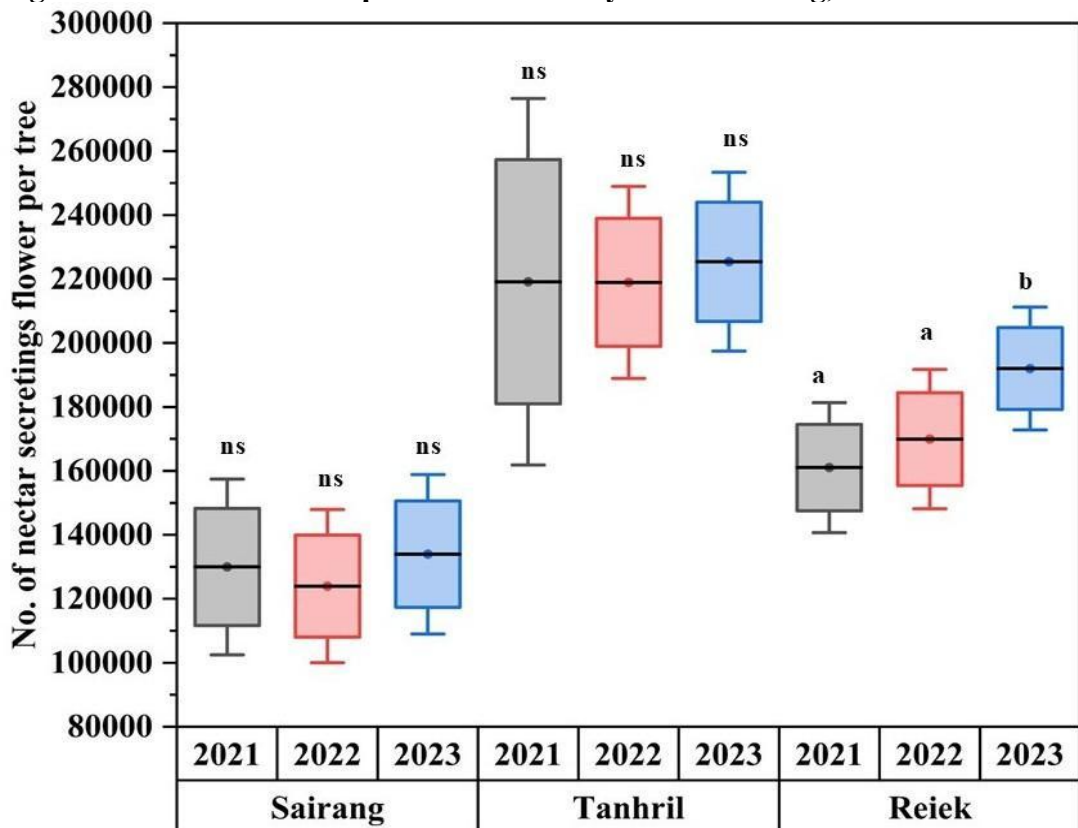


Figure 5.57. No. of nectar secreting flowers per tree for three years in Sairang, Tanhril and Reiek.

significant difference was detected between 2021 and 2022, suggesting that the most notable increase in flower production occurred between 2022 and 2023. Collectively, these findings highlight the temporal variability in flower production across the three sites, with Sairang showing a recovery in 2023, Tanhril exhibiting stability, and Reiek displaying significant growth in flower abundance over the study period.

5.7.1.2.8. No. of nectar secreting flowers per tree

The temporal patterns of nectar-secreting flower production per tree across the sites of Sairang, Tanhril, and Reiek from 2021 to 2023 reveal site-specific variations in flower abundance. In Sairang, the mean number of nectar-secreting flowers per tree exhibited a decrease from $1.30 \pm 0.18 \times 10^5$ in 2021 to $1.24 \pm 0.16 \times 10^5$ in 2022, followed by an increase to $1.34 \pm 0.17 \times 10^5$ in 2023 (Figure 5.57.). Despite these fluctuations, statistical analysis revealed no significant differences between the years at the 0.05 significance level, suggesting that the variations in flower production were not statistically meaningful. Similarly, in Tanhril, the number of nectar-secreting flowers per tree remained relatively stable, with mean values of $2.19 \pm 0.38 \times 10^5$ in 2021, $2.18 \pm 0.20 \times 10^5$ in 2022, and $2.25 \pm 0.19 \times 10^5$ in 2023 (Figure 5.57.). The statistical analysis confirmed that there were no significant differences between the years, indicating a consistent trend in nectar production across the three years. In Reiek, however, a distinct upward trend was observed. The mean number of nectar-secreting flowers per tree increased from $1.61 \pm 0.14 \times 10^5$ in 2021 to $1.70 \pm 0.14 \times 10^5$ in 2022, and further to $1.92 \pm 0.12 \times 10^5$ in 2023 (Figure 5.57.). Statistical testing revealed a significant difference between 2023 and both 2021 and 2022, suggesting a marked increase in nectar-secreting flower production over the study period. However, no significant difference was found between 2021 and 2022, indicating that the substantial increase in nectar-secreting flowers primarily occurred between 2022 and 2023. These results indicate that while nectar-secreting flower production in Sairang and Tanhril remained relatively stable across the years, Reiek demonstrated a significant increase in 2023. The findings highlight site-specific differences in nectar-secreting flower production trends and suggest that ecological or environmental factors may influence nectar-secreting flower production patterns over time.

5.7.1.2.9. No. of hermaphrodite flowers per tree

The temporal patterns of hermaphrodite flower production per tree across the sites of Sairang, Tanhril, and Reiek over a three-year period (2021–2023) reveal distinct trends in flower abundance. In Sairang, the mean number of hermaphrodite flowers per tree decreased from $8.74 \pm 1.14 \times 10^5$ in 2021 to $8.39 \pm 1.07 \times 10^5$ in 2022, followed by an increase to $9.60 \pm 1.43 \times 10^5$ in 2023 (Figure 5.58.). Despite these fluctuations, statistical analysis showed no significant differences between the years at the 0.05 significance level, indicating that the changes in flower production were not statistically significant. A similar pattern was observed in Tanhril, where the mean number of hermaphrodite flowers per tree was $15.26 \pm 2.40 \times 10^5$ in 2021, $14.87 \pm 1.16 \times 10^5$ in 2022, and $15.53 \pm 1.67 \times 10^5$ in 2023 (Figure 5.58.). Statistical testing revealed no significant differences between the years, suggesting a stable trend in flower production at this site. In Reiek, however, a more pronounced increase in flower production was observed. The no. of flowers per tree increased from $11.35 \pm 1.17 \times 10^5$ in 2021 to $11.45 \pm 0.66 \times 10^5$ in 2022 and further rose to $12.63 \pm 0.72 \times 10^5$ in 2023 (Figure 5.58.). Statistical analysis indicated significant differences between 2023 and both 2021 and 2022, suggesting a substantial increase in flower production in the final year of the study. However, no significant difference was found between 2021 and 2022, indicating that the increase in flower production primarily occurred between 2022 and 2023. These findings highlight that while Sairang and Tanhril exhibited stable flower production over time, Reiek experienced a significant increase in flower abundance during the later stages of the study period. The observed site-specific differences in flower production underscore the potential influence of environmental and ecological factors.

5.7.1.2.10. No. of pollen per hermaphrodite flower

The examination of total pollen per hermaphrodite flower across the three sites - Sairang, Tanhril, and Reiek over the period from 2021 to 2023 reveals significant temporal variation in pollen production patterns. In Sairang, the no. of pollen grains per hermaphrodite flower decreased from 380.00 ± 28.03 in 2021 to 353.33 ± 22.57 in 2022, followed by an increase to 398.67 ± 37.20 in 2023 (Figure 5.59.). Statistical

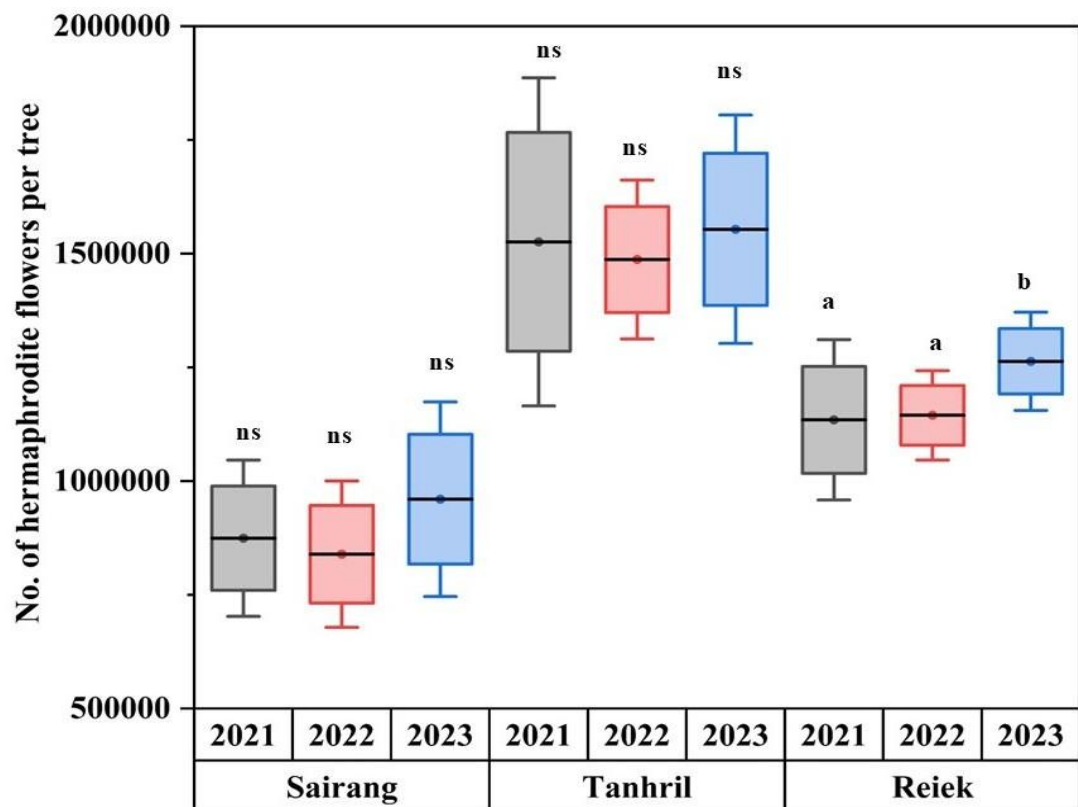


Figure 5.58. No. of hermaphrodite flowers per tree for three years in Sairang, Tanhril and Reiek.

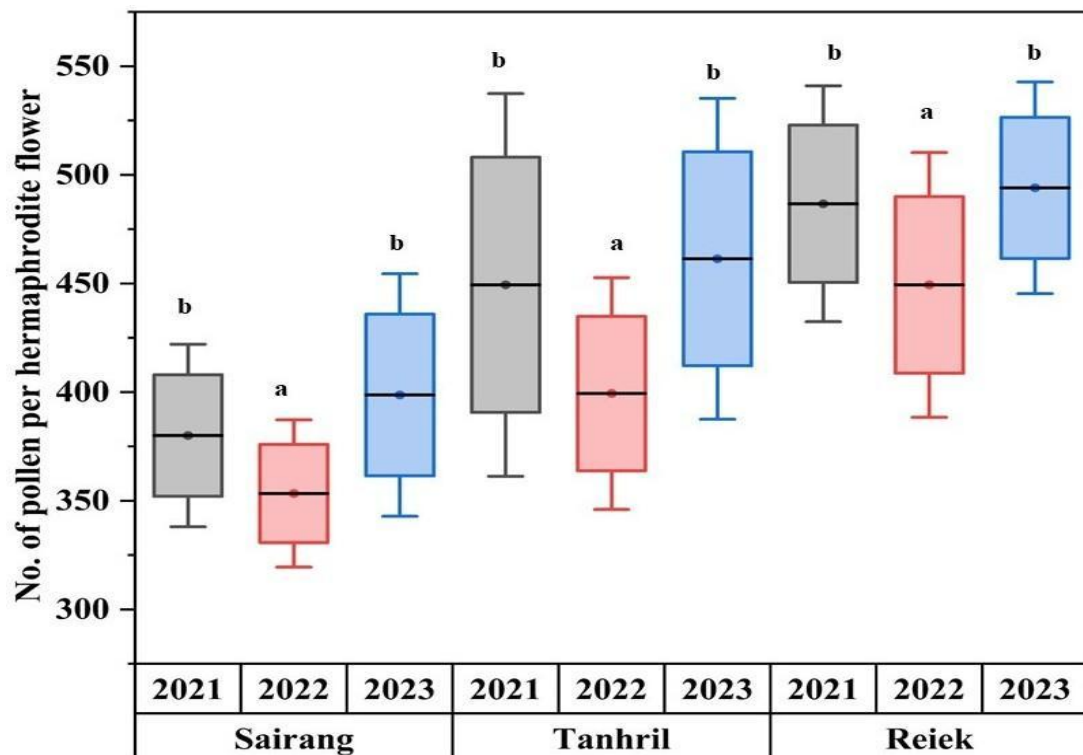


Figure 5.59. No. of pollen per hermaphrodite flower for three years in Sairang, Tanhril and Reiek

analysis demonstrated significant differences between 2022 and both 2021 and 2023, but no significant difference was found between 2021 and 2023, indicating that the decline observed in 2022 was not sustained, and pollen production rebounded to levels comparable to 2021. Similarly, in Tanhril, the mean number of pollen grains per hermaphrodite flower decreased from 449.33 ± 58.73 in 2021 to 399.33 ± 35.55 in 2022, before rising to 461.33 ± 49.26 in 2023 (Figure 5.59.). Statistical tests confirmed significant differences between 2022 and both 2021 and 2023, with no significant difference between 2021 and 2023, reflecting a recovery in pollen production by the final year of the study. In Reiek, the mean pollen count decreased from 486.67 ± 36.19 in 2021 to 449.33 ± 40.61 in 2022, followed by an increase to 494.00 ± 32.47 in 2023 (Figure 5.59.). Significant differences were found between 2022 and both 2021 and 2023, but no significant difference was detected between 2021 and 2023, suggesting that, like the other sites, pollen production returned to levels comparable to 2021 by 2023. These results collectively suggest that while 2022 exhibited a marked decline in pollen production across all three sites, significant recoveries in 2023 indicate that the observed decrease may have been a transient anomaly.

5.7.1.2.11. No. of pollen per inflorescence

The examination of total pollen production per inflorescence across three sites - Sairang, Tanhril, and Reiek over the years 2021 to 2023 highlights significant temporal fluctuations in pollen abundance. In Sairang, the no. of pollen grains per inflorescence decreased from $7.65 \pm 0.94 \times 10^5$ in 2021 to $7.03 \pm 0.85 \times 10^5$ in 2022, followed by a substantial increase to $8.67 \pm 0.99 \times 10^5$ in 2023 (Figure 5.60.). Statistical analysis revealed significant differences between 2022 and both 2021 and 2023 at the 0.01 significance level, suggesting that the decrease in 2022 was an anomaly, with pollen production rebounding to higher levels in 2023. In Tanhril, the mean pollen count per inflorescence exhibited a similar pattern, with a decrease from $11.57 \pm 1.60 \times 10^5$ in 2021 to $10.28 \pm 1.10 \times 10^5$ in 2022, and a subsequent increase to $12.06 \pm 1.77 \times 10^5$ in 2023 (Figure 5.60.). Significant differences were observed between 2022 and both 2021 and 2023, but no significant difference was found between 2021 and 2023, indicating that pollen production in 2023 returned to levels comparable to 2021.

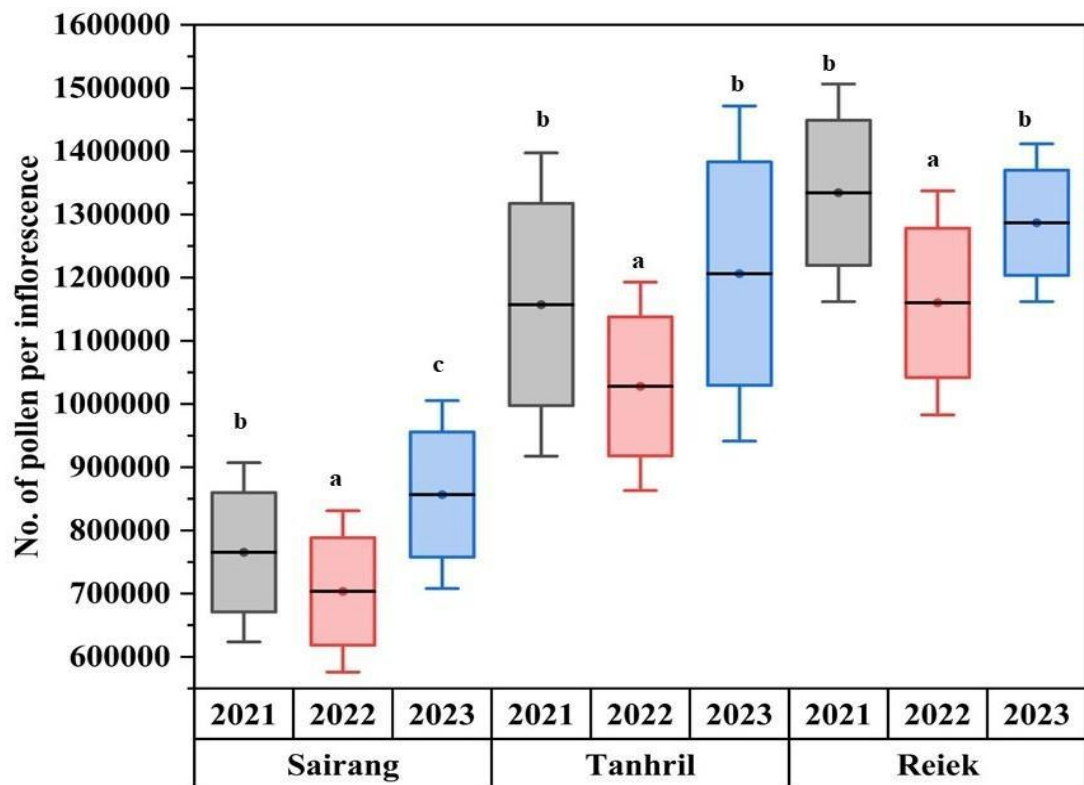


Figure 5.60. No. of pollen per inflorescence for three years in Sairang, Tanhril and Reiek.

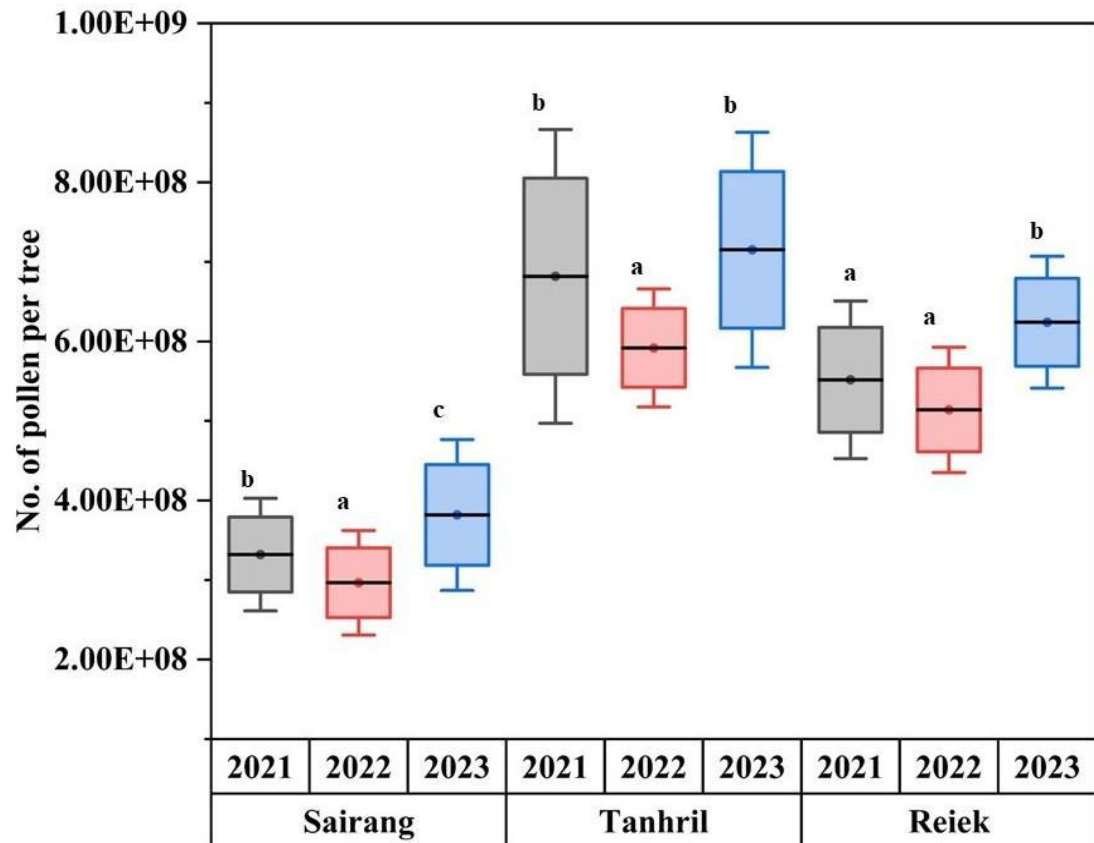


Figure 5.61. No. of pollen per tree for three years in Sairang, Tanhril and Reiek.

Similarly, in Reiek, the mean pollen production decreased from $13.34 \pm 1.15 \times 10^5$ in 2021 to $11.60 \pm 1.18 \times 10^5$ in 2022 and increased again to $12.87 \pm 0.83 \times 10^5$ in 2023 (Figure 5.60.). Statistical analysis confirmed significant differences between 2022 and both 2021 and 2023, with no significant difference between 2021 and 2023, indicating a recovery in pollen production by 2023. These findings underscore the variability in pollen production across the sites, with a notable decrease in 2022 followed by a recovery in 2023, suggesting that transient environmental factors may have influenced pollen production in the second year of the study.

5.7.1.2.12. No. of pollen per tree

The temporal variation in pollen counts across different years (2021–2023) was assessed for three distinct sites: Sairang, Tanhril, and Reiek. In Sairang, the mean total pollen count per tree was $3.31 \pm 0.47 \times 10^8$ in 2021, $2.96 \pm 0.43 \times 10^8$ in 2022, and $3.81 \pm 0.63 \times 10^8$ in 2023 (Figure 5.61.). Statistical analysis revealed a significant difference between these years at the 0.01 level, indicating considerable interannual variability in pollen production. Similarly, in Tanhril, the mean pollen count in 2021 was $6.81 \pm 1.23 \times 10^8$, which decreased to $5.91 \pm 0.49 \times 10^8$ in 2022, before increasing again to $7.15 \pm 0.98 \times 10^8$ in 2023 (Figure 5.61.). A significant difference was found between 2022 and both 2021 and 2023 at the 0.01 level, but no significant difference was observed between 2021 and 2023, suggesting stability in pollen counts between these two years. In Reiek, the mean pollen count was $5.51 \pm 0.66 \times 10^8$ in 2021, $5.14 \pm 0.52 \times 10^8$ in 2022, and $6.24 \pm 0.55 \times 10^8$ in 2023 (Figure 5.61.). Statistically, significant differences were detected between 2023 and both 2021 and 2022, but no significant difference was found between 2021 and 2022. These findings underscore the temporal dynamics of pollen distribution across different regions, with varying levels of interannual variation and associated standard deviations. The significant differences observed at the 0.01 level offer important insights into the ecological factors affecting pollen production, contributing to a deeper understanding of environmental patterns and processes in these regions.

5.7.1.2.13. No. of ovules per flower

The number of ovules per flower was analyzed across three sites - Sairang, Tanhril, and Reiek during the years 2021, 2022, and 2023. In Sairang, the mean ovule count per flower in 2021 was 14.47 ± 1.60 , which decreased slightly to 14.13 ± 2.00 in 2022, before increasing to 15.07 ± 1.58 in 2023 (Figure 5.62.). However, statistical analysis revealed no significant differences in ovule count between the years at the 0.05 level, indicating a stable trend in ovule production across the three years in Sairang. In Tanhril, the mean ovule count per flower was 16.73 ± 2.40 in 2021, 15.47 ± 1.77 in 2022, and 17.67 ± 0.98 in 2023 (Figure 5.62.). A significant difference was observed between 2023 and both 2021 and 2022 at the 0.01 level, but there was no significant difference between 2021 and 2022, suggesting that ovule production in Tanhril exhibited notable fluctuations over the study period. In Reiek, the mean ovule count per flower was 17.47 ± 2.39 in 2021, 17.07 ± 2.89 in 2022, and 17.93 ± 2.05 in 2023 (Figure 5.62.). Similar to Sairang, no significant differences were found between the years at the 0.05 level, indicating stable ovule production in Reiek. These findings suggest that while ovule counts remained relatively stable in Sairang and Reiek, significant temporal variation was observed in Tanhril. Such patterns could be indicative of region-specific environmental factors influencing reproductive processes, and further investigation may be required to better understand the underlying ecological dynamics.

5.7.1.2.14. Pollen ovule ratio

The pollen-ovule ratio (P/O) was examined for three sites - Sairang, Tanhril, and Reiek over the years 2021, 2022, and 2023 to understand the temporal variation in reproductive strategies. In Sairang, the mean P/O was 26.54 ± 3.24 in 2021, decreased to 25.52 ± 4.34 in 2022, and slightly increased to 26.77 ± 3.95 in 2023 (Figure 5.63.). Tanhril showed a mean P/O of 27.53 ± 6.33 in 2021, which dropped to 26.12 ± 3.82 in 2022, and then marginally increased to 26.17 ± 2.97 in 2023 (Figure 5.63.). In Reiek, the mean P/O was 28.34 ± 4.25 in 2021, decreased to 27.02 ± 4.77 in 2022, and increased to 27.89 ± 3.72 in 2023 (Figure 5.63.). Despite these fluctuations, statistical analysis revealed no significant differences in the P/O ratio between the years at the

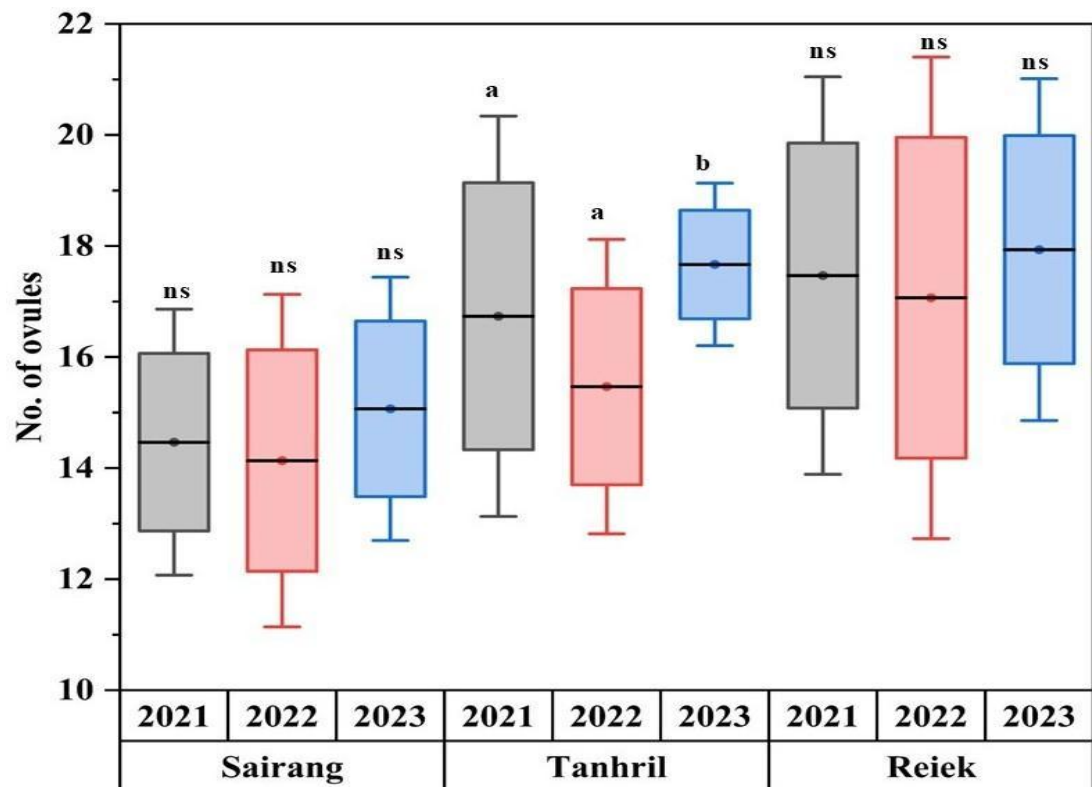


Figure 5.62. No. of ovules per flower for three years in Sairang, Tanhril and Reiek.

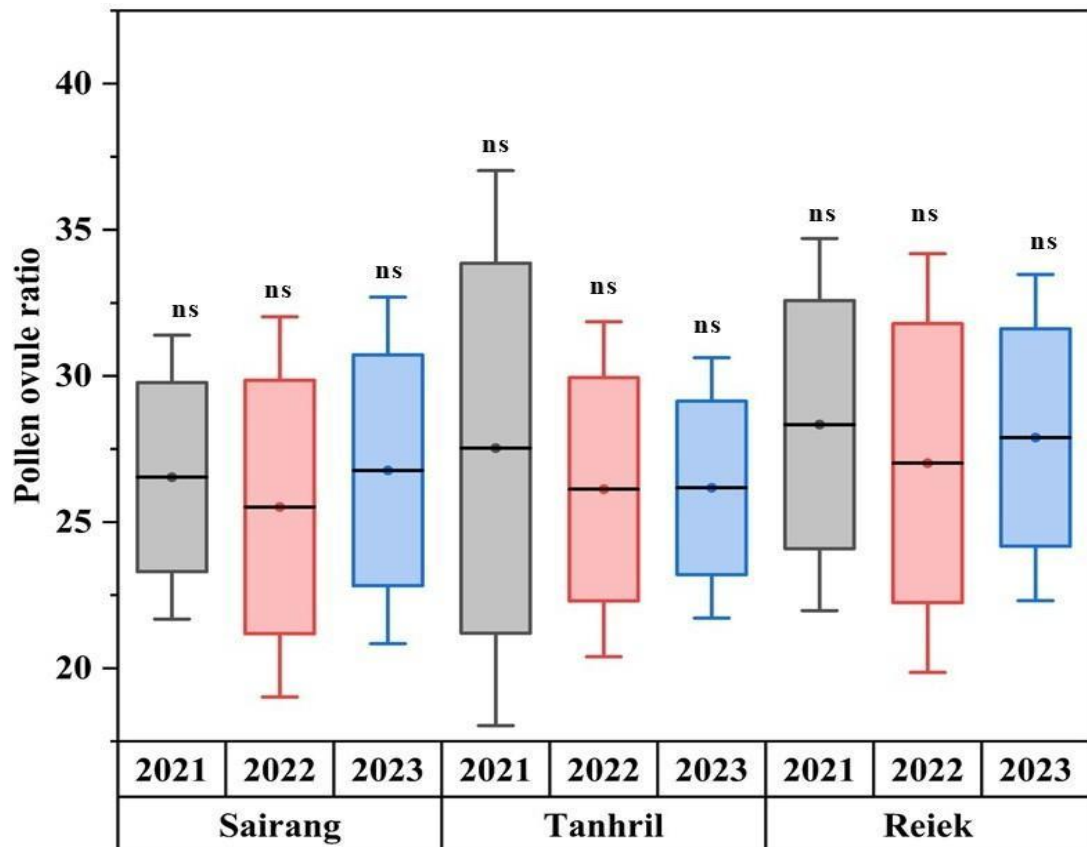


Figure 5.63. Pollen ovule ratio for three years in Sairang, Tanhril and Reiek.

0.05 significance level across all sites. This lack of significant temporal variation suggests that the pollen-ovule ratio in these regions remains stable over time, indicating that reproductive strategies associated with pollen and ovule production are relatively consistent across the three years. These findings are important as they provide insight into the stability of reproductive traits in these regions, offering a broader understanding of the ecological factors that influence such traits.

5.7.1.2.15. Spearman's rank correlation analysis between floral and pollen productivity for Sairang, Tanhril, and Reiek.

Spearman's rank correlation analysis for Sairang revealed several significant positive relationships among key floral traits. The total no. of flowers per tree showed a strong positive correlation with both the no. of inflorescences per tree ($r_s = 0.760^{**}, p < 0.01$) and flowers per inflorescence ($r_s = 0.677^{**}, p < 0.01$), indicating that increased inflorescence and flower numbers contribute significantly to overall flower production. Additionally, a highly significant positive correlation was observed between the total no. of nectar-secreting flowers per tree and inflorescences per tree ($r_s = 0.834^{**}, p < 0.01$), reflecting the pivotal role of nectar-secreting flowers in overall reproductive success (Table 5.14.). The total no. of hermaphrodite flowers per tree also demonstrated a very strong positive correlation with total flowers per tree ($r_s = 0.993^{**}, p < 0.01$), highlighting the close relationship between hermaphrodite flower production and overall flower quantity (Table 5.14.). Further, total pollen per inflorescence was positively correlated with total pollen per tree ($r_s = 0.837^{**}, p < 0.01$), emphasizing the role of individual inflorescences in contributing to overall pollen output (Table 5.14.).

Spearman's rank correlation analysis for Tanhril revealed significant associations among several floral traits. The total no. of flowers per tree exhibited a strong positive correlation with both total hermaphrodite flowers per tree ($r_s = 0.990^{**}, p < 0.01$) and total pollen per tree ($r_s = 0.570^{**}, p < 0.01$), indicating that higher flower production is closely linked to the production of pollen and hermaphrodite flowers (Table 5.15.). Additionally, a notable positive correlation was observed between total pollen per inflorescence and total pollen per tree ($r_s = 0.787^{**}, p < 0.01$), which suggests that

Table 5.14. Spearman's rank correlation analysis between number of inflorescences per tree, flowers per inflorescence, nectar secreting flowers, hermaphrodite flowers, pollen per anther, total flowers per tree, total nectar secreting flowers per tree, total hermaphrodite flowers per tree, total pollen per hermaphrodite flower, total pollen per inflorescence, and total pollen per tree for Sairang.

	Inflorescences per tree	Flowers per inflorescence	Nectar secreting flowers	Hermaphrodite flowers	Pollen per anther	Total flowers per tree
Inflorescences per tree	1	0.089	0.249	0.066	0.176	0.760**
	-	p = 0.560	p = 0.100	p = 0.667	p = 0.247	p = 0.000
Flowers per inflorescence	0.089	1	-0.029	0.995**	-0.008	0.677**
	p = 0.560	-	p = 0.852	p = 0.000	p = 0.956	p = 0.000
Nectar secreting flowers	0.249	-0.029	1	-0.094	0.208	0.183
	p = 0.100	p = 0.852	-	p = 0.537	p = 0.170	p = 0.229
Hermaphrodite flowers	0.066	0.995**	-0.094	1	-0.023	0.657**
	p = 0.667	p = 0.000	p = 0.537	-	p = 0.882	p = 0.000
Pollen per anther	0.176	-0.008	0.208	-0.023	1	0.126
	p = 0.247	p = 0.956	p = 0.170	p = 0.882	-	p = 0.409
Total flowers per tree	0.760**	0.677**	0.183	0.657**	0.126	1
	p = 0.000	p = 0.000	p = 0.229	p = 0.000	p = 0.409	-
Total nectar secreting flowers per tree	0.834**	0.059	0.692**	0.005	0.189	0.648**
	p = 0.000	p = 0.699	p = 0.000	p = 0.974	p = 0.215	p = 0.000
Total hermaphrodite flowers per tree	0.708**	0.726**	0.108	0.712**	0.107	0.993**
	p = 0.000	p = 0.000	p = 0.480	p = 0.000	p = 0.486	p = 0.000
Total pollen per hermaphrodite flower	0.176	-0.008	0.208	-0.023	1.000**	0.126
	p = 0.247	p = 0.956	p = 0.17	p = 0.882	-	p = 0.409
Total pollen per inflorescence	0.147	0.703**	0.073	0.696**	0.655**	0.567**
	p = 0.334	p = 0.000	p = 0.632	p = 0.000	p = 0.000	p = 0.000
Total pollen per tree	0.637**	0.565**	0.158	0.548**	0.614**	0.836**
	p = 0.000	p = 0.000	p = 0.301	p = 0.000	p = 0.000	p = 0.000

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

	Total nectar secreting flowers per tree	Total hermaphrodite flowers per tree	Total pollen per hermaphrodite flower	Total pollen per inflorescence	Total pollen per tree
Inflorescences per tree	0.834** p = 0.000	0.708** p = 0.000	0.176 p = 0.247	0.147 p = 0.334	0.637** p = 0.000
Flowers per inflorescence	0.059 p = 0.699	0.726** p = 0.000	-0.008 p = 0.956	0.703** p = 0.000	0.565** p = 0.000
Nectar secreting flowers	0.692** p = 0.000	0.108 p = 0.480	0.208 p = 0.170	0.073 p = 0.632	0.158 p = 0.301
Hermaphrodite flowers	0.005 p = 0.974	0.712** p = 0.000	-0.023 p = 0.882	0.696** p = 0.000	0.548** p = 0.000
Pollen per anther	0.189 p = 0.215	0.107 p = 0.486	1.000** -	0.655** p = 0.000	0.614** p = 0.000
Total flowers per tree	0.648** p = 0.000	0.993** p = 0.000	0.126 p = 0.409	0.567** p = 0.000	0.836** p = 0.000
Total nectar secreting flowers per tree	1 -	0.573** p = 0.000	0.189 p = 0.215	0.100 p = 0.513	0.513** p = 0.000
Total hermaphrodite flowers per tree	0.573** p = 0.000	1 -	0.107 p = 0.486	0.590** p = 0.000	0.830** p = 0.000
Total pollen per hermaphrodite flower	0.189 p = 0.215	0.107 p = 0.486	1 -	0.655** p = 0.000	0.614** p = 0.000
Total pollen per inflorescence	0.100 p = 0.513	0.590** p = 0.000	0.655** p = 0.000	1 -	0.837** p = 0.000
Total pollen per tree	0.513** p = 0.000	0.830** p = 0.000	0.614** p = 0.000	0.837** p = 0.000	1 -
** Correlation is significant at the 0.01 level.					
* Correlation is significant at the 0.05 level.					

Table 5.15. Spearman's rank correlation analysis between number of inflorescences per tree, flowers per inflorescence, nectar secreting flowers, hermaphrodite flowers, pollen per anther, total flowers per tree, total nectar secreting flowers per tree, total hermaphrodite flowers per tree, total pollen per hermaphrodite flower, total pollen per inflorescence, and total pollen per tree for Tanhril.

	Inflorescences per tree	Flowers per inflorescence	Nectar secreting flowers	Hermaphrodite flowers	Pollen per anther	Total flowers per tree
Inflorescences per tree	1	-0.301*	-0.111	-0.257	-0.022	0.580**
	-	p = 0.045	p = 0.469	p = 0.088	p = 0.884	p = 0.000
Flowers per inflorescence	-0.301*	1	0.117	0.974**	-0.050	0.537**
	p = 0.045	-	p = 0.445	p = 0.000	p = 0.743	p = 0.000
Nectar secreting flowers	-0.111	0.117	1	-0.002	-0.070	0.034
	p = 0.469	p = 0.445	-	p = 0.99	p = 0.647	p = 0.826
Hermaphrodite flowers	-0.257	0.974**	-0.002	1	-0.085	0.572**
	p = 0.088	p = 0.000	p = 0.99	-	p = 0.579	p = 0.000
Pollen per anther	-0.022	-0.050	-0.070	-0.085	1	-0.105
	p = 0.884	p = 0.743	p = 0.647	p = 0.579	-	p = 0.492
Total flowers per tree	0.580**	0.537**	0.034	0.572**	-0.105	1
	p = 0.000	p = 0.000	p = 0.826	p = 0.000	p = 0.492	-
Total nectar secreting flowers per tree	0.515**	-0.055	0.717**	-0.137	-0.022	0.417**
	p = 0.000	p = 0.721	p = 0.000	p = 0.370	p = 0.885	p = 0.004
Total hermaphrodite flowers per tree	0.546**	0.571**	-0.053	0.618**	-0.095	0.990**
	p = 0.000	p = 0.000	p = 0.731	p = 0.000	p = 0.536	p = 0.000
Total pollen per hermaphrodite flower	-0.022	-0.050	-0.070	-0.085	1.000**	-0.105
	p = 0.884	p = 0.743	p = 0.647	p = 0.579	.	p = 0.492
Total pollen per inflorescence	-0.230	0.550**	0.001	0.510**	0.762**	0.227
	p = 0.129	p = 0.000	p = 0.994	p = 0.000	p = 0.000	p = 0.133
Total pollen per tree	0.325*	0.401**	-0.046	0.404**	0.670**	0.570**
	p = 0.029	p = 0.006	p = 0.762	p = 0.006	p = 0.000	p = 0.000

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

	Total nectar secreting flowers per tree	Total hermaphrodite flowers per tree	Total pollen per hermaphrodite flower	Total pollen per inflorescence	Total pollen per tree
Inflorescences per tree	0.515** p = 0.000	0.546** p = 0.000	-0.022 p = 0.884	-0.23 p = 0.129	0.325* p = 0.029
Flowers per inflorescence	-0.055 p = 0.721	0.571** p = 0.000	-0.050 p = 0.743	0.550** p = 0.000	0.401** p = 0.006
Nectar secreting flowers	0.717** p = 0.000	-0.053 p = 0.731	-0.070 p = 0.647	0.001 p = 0.994	-0.046 p = 0.762
Hermaphrodite flowers	-0.137 p = 0.37	0.618** p = 0.000	-0.085 p = 0.579	0.510** p = 0.000	0.404** p = 0.006
Pollen per anther	-0.022 p = 0.885	-0.095 p = 0.536	1.000** .	0.762** p = 0.000	0.670** p = 0.000
Total flowers per tree	0.417** p = 0.004	0.990** p = 0.000	-0.105 p = 0.492	0.227 p = 0.133	0.570** p = 0.000
Total nectar secreting flowers per tree	1 -	0.321* p = 0.032	-0.022 p = 0.885	-0.100 p = 0.512	0.202 p = 0.184
Total hermaphrodite flowers per tree	0.321* p = 0.032	1 -	-0.095 p = 0.536	0.260 p = 0.084	0.581** p = 0.000
Total pollen per hermaphrodite flower	-0.022 p = 0.885	-0.095 p = 0.536	1 -	0.762** p = 0.000	0.670** p = 0.000
Total pollen per inflorescence	-0.100 p = 0.512	0.260 p = 0.084	0.762** p = 0.000	1 -	0.787** p = 0.000
Total pollen per tree	0.202 p = 0.184	0.581** p = 0.000	0.670** p = 0.000	0.787** p = 0.000	1 -
** Correlation is significant at the 0.01 level.					
* Correlation is significant at the 0.05 level.					

Table 5.16. Spearman's rank correlation analysis between number of inflorescences per tree, flowers per inflorescence, nectar secreting flowers, hermaphrodite flowers, pollen per anther, total flowers per tree, total nectar secreting flowers per tree, total hermaphrodite flowers per tree, total pollen per hermaphrodite flower, total pollen per inflorescence, and total pollen per tree for Reiek.

	Inflorescences per tree	Flowers per inflorescence	Nectar secreting flowers	Hermaphrodite flowers	Pollen per anther	Total flowers per tree
Inflorescences per tree	1	-0.343*	0.010	-0.365*	0.123	0.852**
	-	p = 0.021	p = 0.947	p = 0.014	p = 0.421	p = 0.000
Flowers per inflorescence	-0.343*	1	0.049	0.976**	0.088	0.142
	p = 0.021	-	p = 0.748	p = 0.000	p = 0.566	p = 0.353
Nectar secreting flowers	0.010	0.049	1	-0.099	0.150	0.055
	p = 0.947	p = 0.748	-	p = 0.519	p = 0.325	p = 0.717
Hermaphrodite flowers	-0.365*	0.976**	-0.099	1	0.059	0.11
	p = 0.014	p = 0.000	p = 0.519	-	p = 0.702	p = 0.471
Pollen per anther	0.123	0.088	0.150	0.059	1	0.189
	p = 0.421	p = 0.566	p = 0.325	p = 0.702	-	p = 0.214
Total flowers per tree	0.852**	0.142	0.055	0.110	0.189	1
	p = 0.000	p = 0.353	p = 0.717	p = 0.471	p = 0.214	-
Total nectar secreting flowers per tree	0.883**	-0.237	0.414**	-0.322*	0.226	0.815**
	p = 0.000	p = 0.117	p = 0.005	p = 0.031	p = 0.136	p = 0.000
Total hermaphrodite flowers per tree	0.792**	0.226	-0.051	0.209	0.191	0.985**
	p = 0.000	p = 0.135	p = 0.737	p = 0.169	p = 0.208	p = 0.000
Total pollen per hermaphrodite flower	0.123	0.088	0.150	0.059	1.000**	0.189
	p = 0.421	p = 0.566	p = 0.325	p = 0.702	.	p = 0.214
Total pollen per inflorescence	-0.048	0.592**	0.070	0.571**	0.791**	0.289
	p = 0.754	p = 0.000	p = 0.650	p = 0.000	p = 0.000	p = 0.054
Total pollen per tree	0.601**	0.241	0.099	0.207	0.734**	0.772**
	p = 0.000	p = 0.111	p = 0.518	p = 0.172	p = 0.000	p = 0.000

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

	Total secreting per tree	nectar flowers	Total hermaphrodite flowers per tree	Total pollen per hermaphrodite flower	Total pollen per inflorescence	Total pollen per tree
Inflorescences per tree	0.883**		0.792**	0.123	-0.048	0.601**
	p = 0.000		p = 0.000	p = 0.421	p = 0.754	p = 0.000
Flowers per inflorescence	-0.237		0.226	0.088	0.592**	0.241
	p = 0.117		p = 0.135	p = 0.566	p = 0.000	p = 0.111
Nectar secreting flowers	0.414**		-0.051	0.150	0.070	0.099
	p = 0.005		p = 0.737	p = 0.325	p = 0.65	p = 0.518
Hermaphrodite flowers	-0.322*		0.209	0.059	0.571**	0.207
	p = 0.031		p = 0.169	p = 0.702	p = 0.000	p = 0.172
Pollen per anther	0.226		0.191	1.000**	0.791**	0.734**
	p = 0.136		p = 0.208	.	p = 0.000	p = 0.000
Total flowers per tree	0.815**		0.985**	0.189	0.289	0.772**
	p = 0.000		p = 0.000	p = 0.214	p = 0.054	p = 0.000
Total nectar secreting flowers per tree	1		0.718**	0.226	0.063	0.633**
	-		p = 0.000	p = 0.136	p = 0.681	p = 0.000
Total hermaphrodite flowers per tree	0.718**		1	0.191	0.345*	0.777**
	p = 0.000		-	p = 0.208	p = 0.020	p = 0.000
Total pollen per hermaphrodite flower	0.226		0.191	1	0.791**	0.734**
	p = 0.136		p = 0.208	-	p = 0.000	p = 0.000
Total pollen per inflorescence	0.063		0.345*	0.791**	1	0.743**
	p = 0.681		p = 0.020	p = 0.000	-	p = 0.000
Total pollen per tree	0.633**		0.777**	0.734**	0.743**	1
	p = 0.000		p = 0.000	p = 0.000	p = 0.000	-

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

higher pollen production at the inflorescence level contributes significantly to overall pollen output. The relationship between total pollen per tree and total pollen per anther ($r_s = 0.670^{**}$, $p < 0.01$) further reinforces the idea that an increase in pollen numbers across the tree is driven by pollen per anther (Table 5.15.). Furthermore, the positive correlation between total pollen per inflorescence and total pollen per tree ($r_s = 0.787^{**}$, $p < 0.01$) highlights the importance of overall pollen per inflorescence production as a determinant of total pollen output (Table 5.15.).

Spearman's rank correlation analysis for Reiek demonstrated several significant positive correlations between floral traits. The total number of flowers per tree was positively correlated with both inflorescences per tree ($r_s = 0.852^{**}$, $p < 0.01$) and total nectar secreting flowers per tree ($r_s = 0.815^{**}$, $p < 0.01$), underscoring the importance of overall flower production in driving the numbers of these key reproductive flower types (Table 5.16.). Furthermore, total pollen per inflorescence showed a strong positive correlation with total pollen per tree ($r_s = 0.743^{**}$, $p < 0.01$), suggesting that increased pollen production at the inflorescence level is a key contributor to total pollen output (Table 5.16.). Another strong correlation was observed between total flowers per tree and total pollen per tree ($r_s = 0.772^{**}$, $p < 0.01$), reinforcing the central role of total flowers per tree in overall pollen productivity. The total no. of pollen per inflorescence and total pollen per hermaphrodite flower were also significantly positively correlated ($r_s = 0.791^{**}$, $p < 0.01$), emphasizing the contribution of collective pollen per inflorescence to the overall hermaphrodite flower production in Reiek (Table 5.16.).

5.7.2. Pollen grain size and volume

The pollen grain morphology of *P. timoriana* was assessed by measuring the polar and equatorial dimensions, along with the volume, to provide insights into its reproductive characteristics. The average polar (P) dimension of the pollen grains was recorded at 96.55 μm , while the equatorial (E) dimension was 75.57 μm (Figure 5.64.). The polar dimension exhibited a standard deviation (SD) of 7.92 μm , indicating a moderate variation in size among the grains, whereas the equatorial dimension showed a slightly lower SD of 7.50 μm , suggesting relatively less variation in this axis. The mean

volume of the pollen grains was determined to be $2.90 \times 10^5 \mu\text{m}^3$, with a standard deviation of $0.61 \times 10^5 \mu\text{m}^3$, reflecting notable variability in the overall size of the grains (Figure 5.64.). The larger mean value of the polar dimension compared to the equatorial dimension suggests that the pollen grains of *P. timoriana* tend to be more elongated along the polar axis. These findings provide valuable data on the size distribution and structural characteristics of *P. timoriana* pollen, which may have implications for understanding the plant's pollination biology and its ecological interactions. The observed variability in size also underscores the potential genetic diversity and adaptive mechanisms present within the species.

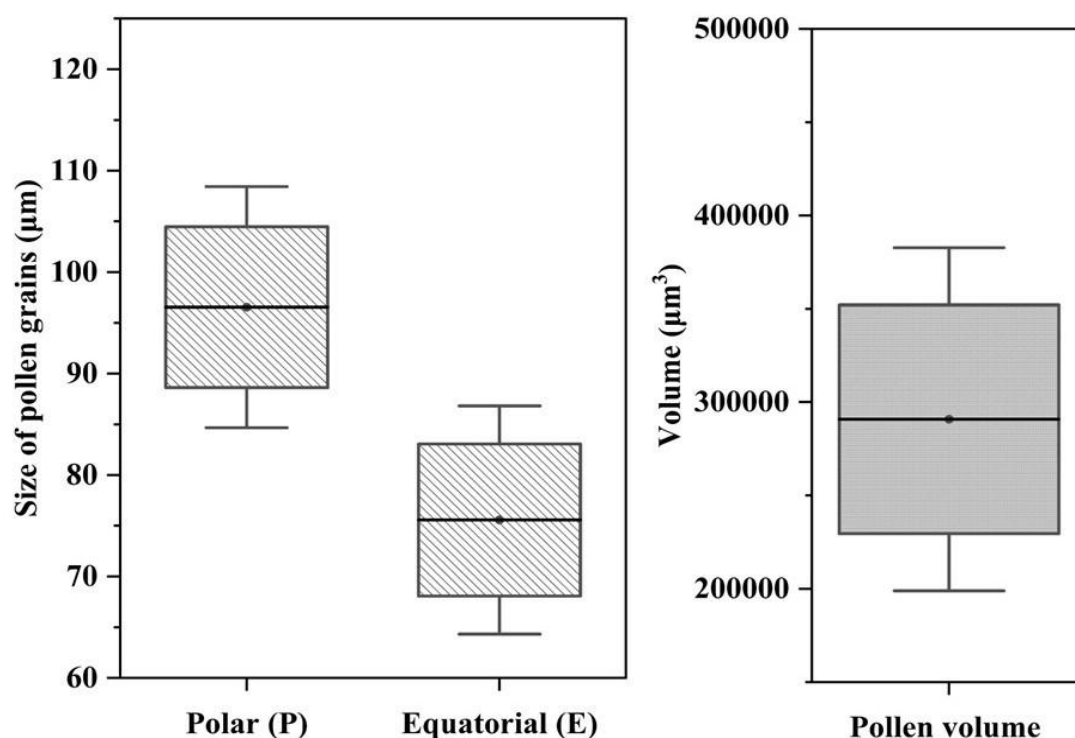


Figure 5.64. Pollen grain size and volume of *P. timoriana*.

5.8. Air-borne pollen density

5.8.1. Slide hanging method

The concentration of pollen grains per square centimeter was recorded across various hourly intervals, revealing significant temporal fluctuations in pollen dispersal patterns throughout the day. In the evening, starting at 19:00-20:00 hr, the concentration was relatively low at 3.38 ± 1.77 , and gradually increased as the night progressed, peaking at 340.82 ± 52.60 during the 05:00-06:00 hr period, indicating the period of maximum

pollen dispersal (Figure 5.65.). This peak was followed by a decline during the morning hours, with concentration of pollen decreasing. Pollen levels continued to decrease through the afternoon, reaching the lowest concentration at 18:00-19:00 hr, with 7.83 ± 7.48 (Figure 5.65.). The results suggest that pollen dispersion follows a diurnal rhythm, with a distinct peak in the early morning hours, potentially affected by climatic variables such as temperature, humidity, and wind patterns, which may facilitate or inhibit the release and movement of pollen. The data underscores the importance of time-of-day in understanding pollen dynamics, providing insights into the mechanisms of pollen dispersal, which are crucial for evaluating pollinator interactions and plant reproductive strategies. These findings underscore the necessity for further investigation into the environmental factors that regulate pollen release and dispersal, and their implications for ecological and agricultural systems.

5.8.2. GRIPS-99M Rotation Impaction Sampler

The concentration of pollen grains per cubic meter was measured across various time blocks, revealing a clear temporal pattern in pollen dispersal. The lowest concentrations were recorded during the evening and early night hours, starting at 19:00-20:00 hr with 3.89 ± 1.97 and gradually increasing as the night progressed (Figure 5.66.). Pollen concentration reached a notable increase at 23:00-24:00 hr (21.38 ± 8.27), followed by a sharp rise during the early morning hours, peaking at 04:00-05:00 hr with 200.57 ± 34.16 , suggesting a strong release of pollen during the cooler, more stable atmospheric conditions of the night (Figure 5.66.). This peak in the early morning hours was followed by a gradual decline in pollen concentration as the day advanced, with levels dropping to 9.55 ± 4.50 by 17:00-18:00 hr and 4.89 ± 2.01 by 18:00-19:00 hr (Figure 5.66.). These fluctuations in pollen concentration indicate a pronounced diurnal pattern, with the highest dispersal occurring at early morning, likely affected by climatic variables such as temperature, humidity, and possibly reduced atmospheric turbulence. Understanding these patterns of pollen dispersal is crucial for insights into plant reproductive dynamics and the timing of pollinator activity, providing a better understanding of ecological interactions and plant-pollinator relationships across different temporal scales.

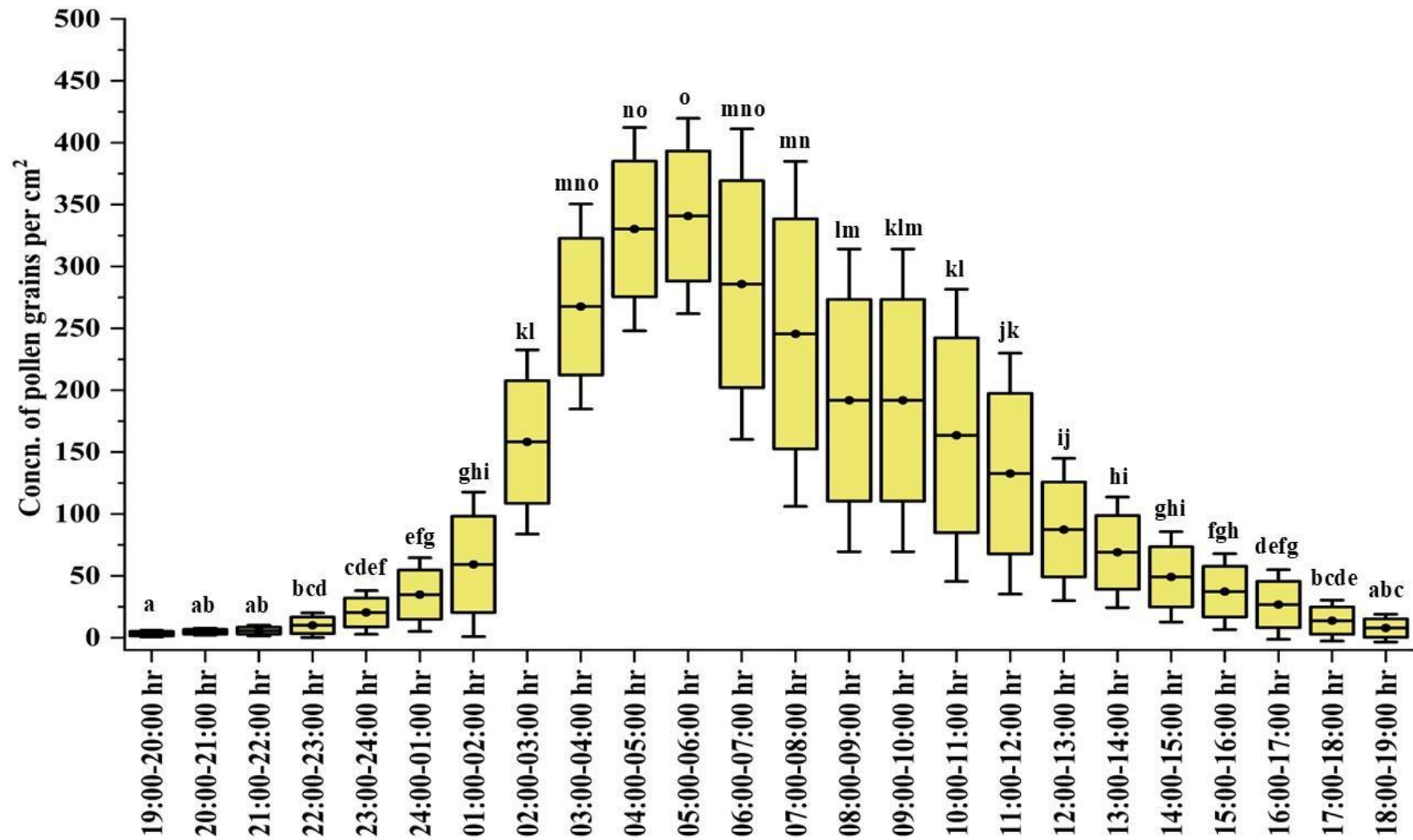


Figure 5.65. Concentration of pollen grains per cm² for each time block.

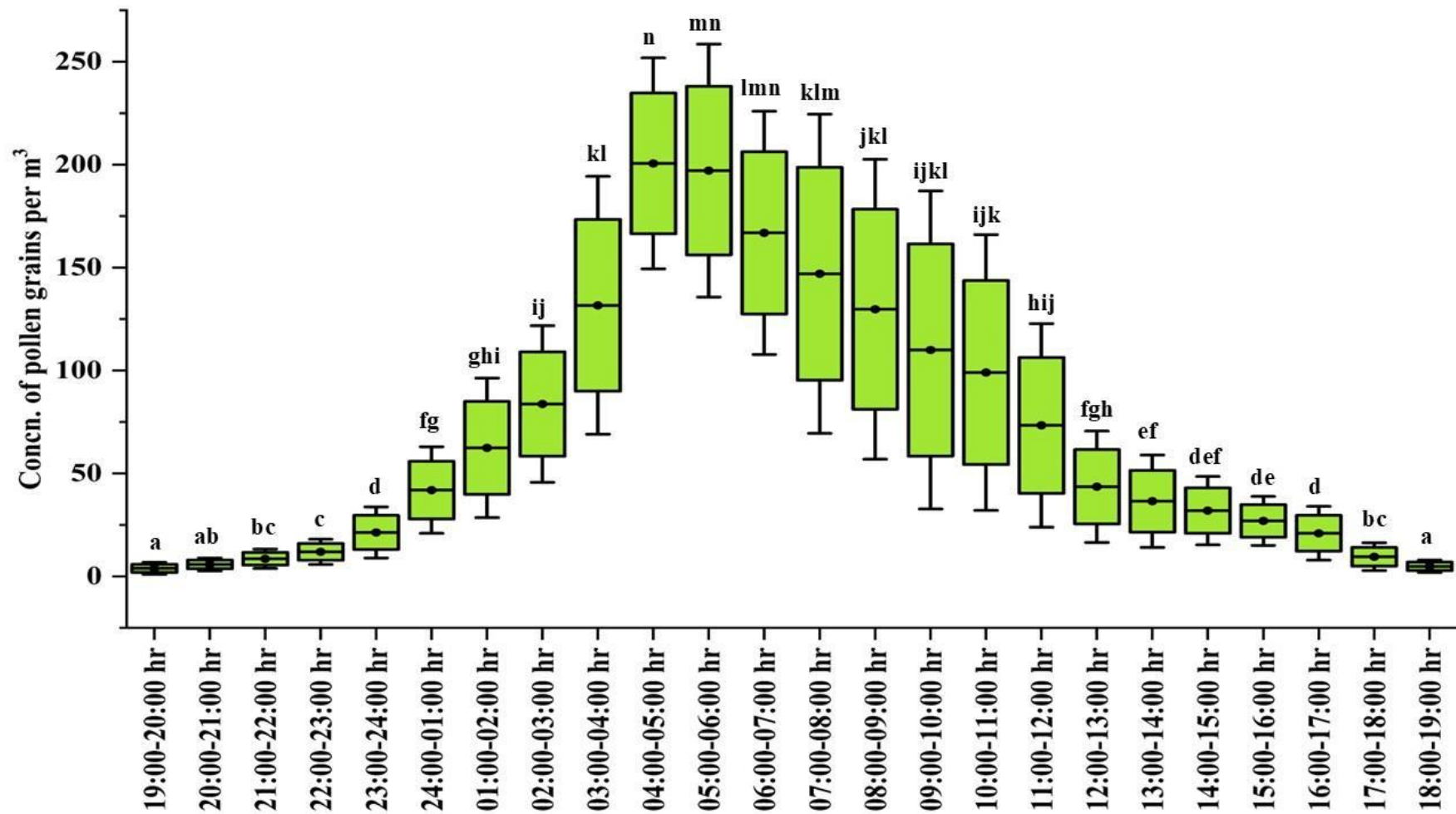


Figure 5.66. Concentration of pollen grains per m³ for each time block.

5.8.3. Spearman's rank correlation analysis between concentration of pollen grains and environmental parameters

Spearman's rank correlation analysis was conducted to investigate the relationships between the concentration of pollen grains and various environmental parameters, including temperature, humidity, precipitation, wind speed, surface pressure, and photosynthetically active radiation (PAR). The results, as shown in Table 5.17., demonstrate several significant associations between these factors and pollen concentration. Both measures of pollen concentration: concentration per cm² and pollen per m³ exhibited strong negative correlations with temperature at 2 meters (TM), dew/frost point at 2 meters (TDEW), wet bulb temperature at 2 meters (TWET), specific humidity at 2 meters (QV), and PAR. Notably, temperature at 2 meters (TM) showed negative correlations with both concentration metrics ($r_s = -0.651^{**}$, $p < 0.01$ for concentration per cm² and $r_s = -0.625^{**}$, $p < 0.01$ for pollen per m³), indicating that higher temperatures are associated with lower pollen concentrations. Similarly, TDEW, TWET, and QV were negatively correlated with both pollen concentration measures, with r_s values ranging from -0.247^{**} to -0.583^{**} ($p < 0.01$), further confirming the inverse relationship between these environmental factors and pollen concentration (Table 5.17). The most striking negative correlation was observed with PAR, where both pollen concentration per cm² ($r_s = -0.828^{**}$, $p < 0.01$) and pollen per m³ ($r_s = -0.870^{**}$, $p < 0.01$) were strongly negatively correlated, suggesting that higher PAR values correspond to a significant reduction in pollen concentrations (Table 5.17). In contrast, relative humidity (RH), surface pressure (PS), and wind speed (WS) exhibited positive correlations with pollen concentration. RH demonstrated a strong positive correlation with both concentration measures, with r_s values of 0.647^{**} ($p < 0.01$) for concentration per cm² and 0.704^{**} ($p < 0.01$) for pollen per m³, indicating that increased humidity enhances pollen concentration (Table 5.17). Similarly, PS and WS showed positive correlations, with r_s values of 0.230^{**} ($p < 0.01$) and 0.567^{**} ($p < 0.01$) for concentration per cm² and 0.219^{**} ($p < 0.01$) and 0.526^{**} ($p < 0.01$) for pollen per m³, respectively, suggesting that changes in

Table 5.17. Spearman's rank correlation analysis between concentration of pollen grains and environmental parameters studied

	Concentration of pollen per cm ²		Pollen per m ³	
	<i>r_s</i>	<i>p</i>	<i>r_s</i>	<i>p</i>
T	0.120	0.063	0.054	0.402
TM	−0.651**	0.000	−0.625**	0.000
TDEW	−0.331**	0.000	−0.249**	0.000
TWET	−0.583**	0.000	−0.533**	0.000
QV	−0.326**	0.000	−0.247**	0.000
RH	0.647**	0.000	0.704**	0.000
PR	0.203**	0.002	0.168**	0.009
PS	0.230**	0.000	0.219**	0.001
WS	0.567**	0.000	0.526**	0.000
PAR	−0.828**	0.000	−0.870**	0.000
Concentration of pollen per cm²	1	-	0.922**	0.000
Pollen per m³	0.922**	0.000	1	-

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

atmospheric pressure and wind speed contribute to the distribution and concentration of pollen. Finally, a very strong positive correlation was found between the two measures of pollen concentration, with $r_s = 0.922^{**}$ ($p < 0.01$), indicating a high degree of consistency between the concentration of pollen per cm² and pollen per m³ (Table 5.17). The findings highlight the intricate interactions between pollen concentration and various environmental parameters, underscoring the importance of temperature, humidity, and atmospheric conditions in regulating pollen dynamics. These results provide critical insights into the environmental factors influencing pollen concentrations, which may be of particular relevance to studies of plant reproduction, and atmospheric biology.

5.9. Analysis of pollen viability

5.9.1. Comparison of pollen viability test by using TTC, FDA, and Alexander staining for hermaphrodite flower and nectar secreting flower.

The comparison of pollen viability percentages for hermaphrodite and nectar-secreting flowers using three different methods - TTC, FDA, and Alexander staining reveals distinct differences in the effectiveness of each technique (Figures 5.67., 5.68. and 5.69.). For the hermaphrodite flower, the pollen viability percentage measured by TTC was 60.35%, which increased to 73.82% when using FDA, and further rose to 77.17% with Alexander staining (Figure 5.70.). This trend indicates that the Alexander staining method consistently produced the highest pollen viability values, followed by FDA, and then TTC. Similarly, for nectar-secreting flowers, the viability percentage followed the same pattern: 44.32% for TTC, 50.39% for FDA, and 60.48% for Alexander staining (Figure 5. 70.). The statistical analysis confirmed significant differences in pollen viability between the three methods at the 0.01 level for both flower types. Additionally, the standard deviation values for the hermaphrodite flower were 2.87, 2.96, and 3.83 for TTC, FDA, and Alexander staining, respectively, indicating a higher variability in the results obtained with Alexander staining. In contrast, the nectar-secreting flowers exhibited lower variability, with standard deviations of 1.92, 2.82, and 2.72 for the same methods.

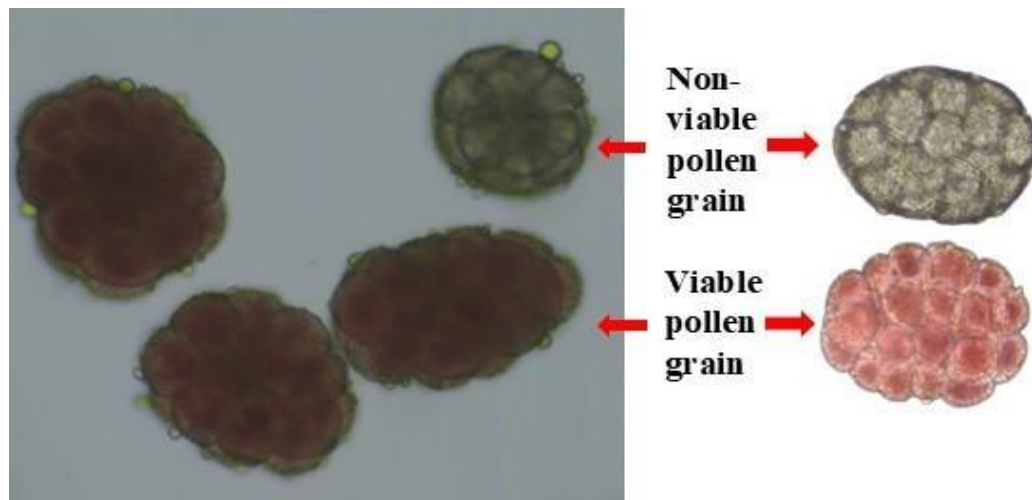


Figure 5.67. Pollen viability test by TTC



Figure 5. 69. Pollen viability test by Alexander staining

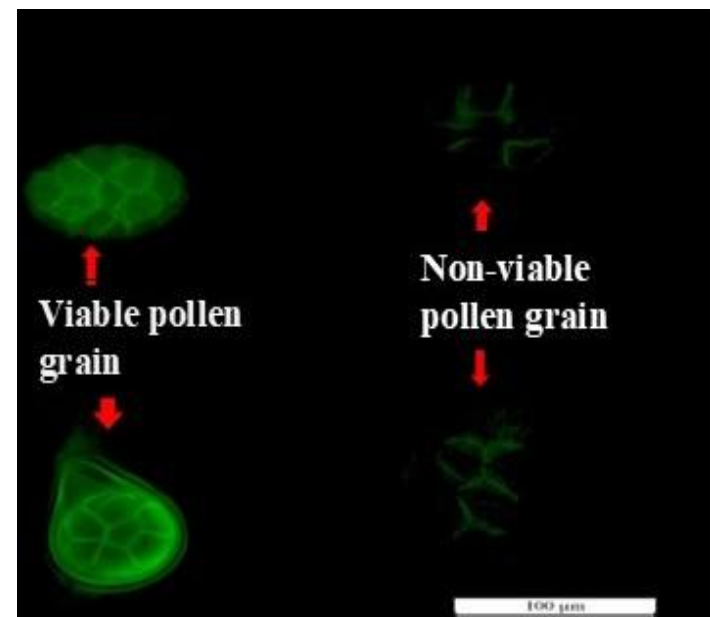


Figure 5.68. Pollen viability test by FDA

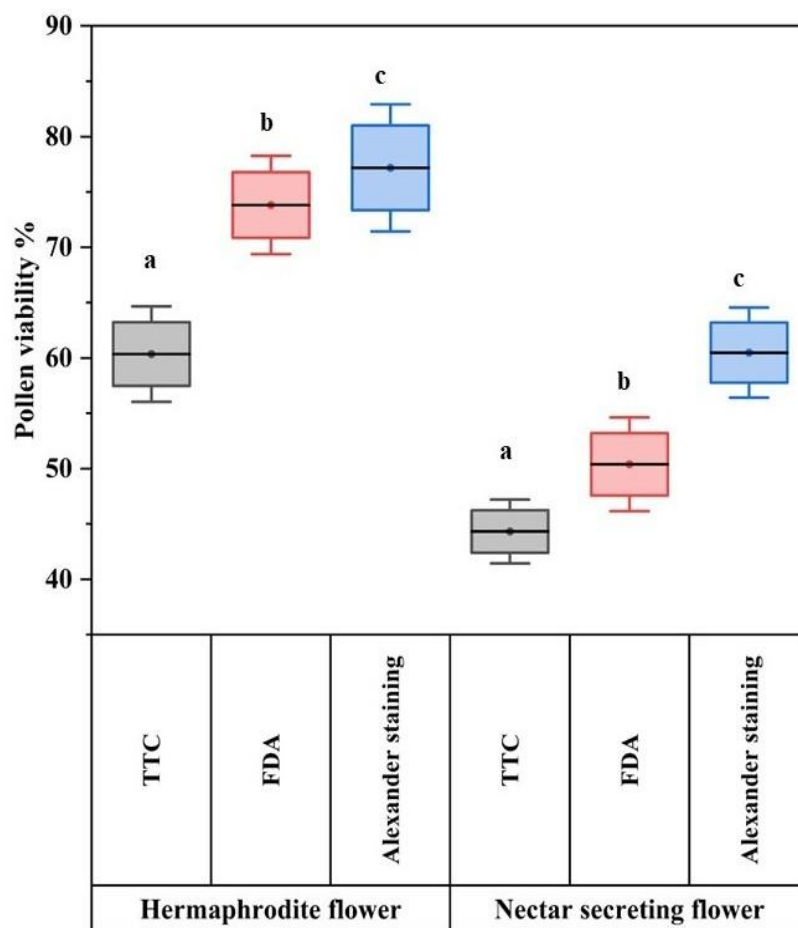


Figure 5.70. Comparison of pollen viability test by using TTC, FDA, and Alexander staining for hermaphrodite flower and nectar secreting flower.

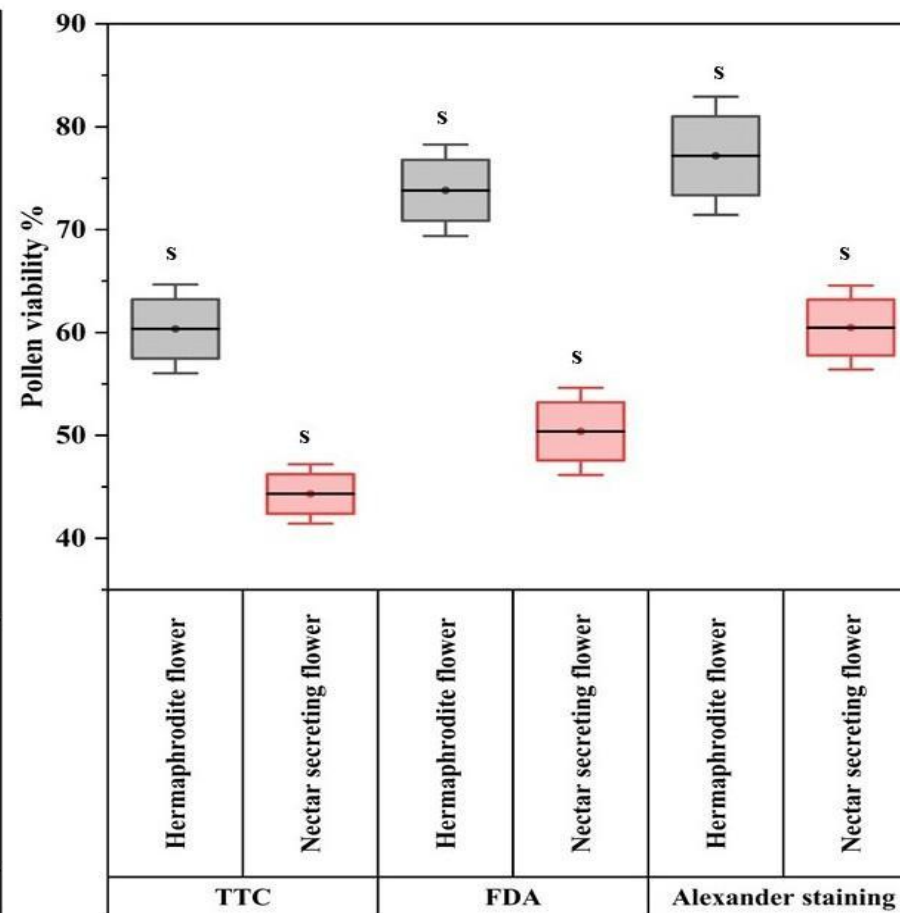


Figure 5.71. Comparison of pollen viability test between hermaphrodite flower and nectar secreting flower.

5.9.2. Comparison of pollen viability test between hermaphrodite flower and nectar secreting flower.

The comparison of pollen viability percentages between hermaphrodite and nectar-secreting flowers using three different methods - TTC, FDA, and Alexander staining demonstrates significant differences in the viability of pollen from these two flower types (Figures 5.67., 5.68. and 5.69.). For the TTC method, the pollen viability for hermaphrodite flowers was 60.35%, significantly higher than the 44.32% observed for nectar-secreting flowers (Figure 5.71.). A similar trend was observed with the FDA method, where the pollen viability for hermaphrodite flowers was 73.82%, compared to 50.39% for nectar-secreting flowers (Figure 5. 71.). The Alexander staining method also showed a higher pollen viability for hermaphrodite flowers (77.17%) compared to nectar-secreting flowers (60.48%) (Figure 5. 71.). The standard deviations for these values were 2.87, 2.96, and 3.83 for hermaphrodite flowers, and 1.92, 2.82, and 2.72 for nectar-secreting flowers for TTC, FDA, and Alexander staining, respectively. The statistical analysis confirmed that in all three methods, there was a significant difference between the pollen viability of hermaphrodite and nectar-secreting flowers at the 0.01 level. These results consistently indicate that hermaphrodite flowers exhibit higher pollen viability across all methods tested, emphasizing the influence of flower type on pollen viability. This study offers important insights into the differential viability of pollen from hermaphrodite and nectar-secreting flowers, which could have implications for reproductive success and plant breeding strategies.

5.10. Nectar analysis

5.10.1. Concentration of nectar

The concentration of nectar of *P. timoriana* was measured across hourly intervals to assess the temporal dynamics of nectar secretion. The highest concentration was observed between 18:00-19:00 hr, with a mean of 20.03 ± 0.26 °Bx, indicating the peak period of nectar secretion (Figure 5.72). Following this, there was a steady decline in nectar concentration throughout the evening, with concentrations decreasing to 18.78 ± 0.90 °Bx during 19:00-20:00 hr, and further to 17.33 ± 0.88 °Bx by 20:00-21:00 hr (Figure 5.72). The concentration continued to decrease through the night

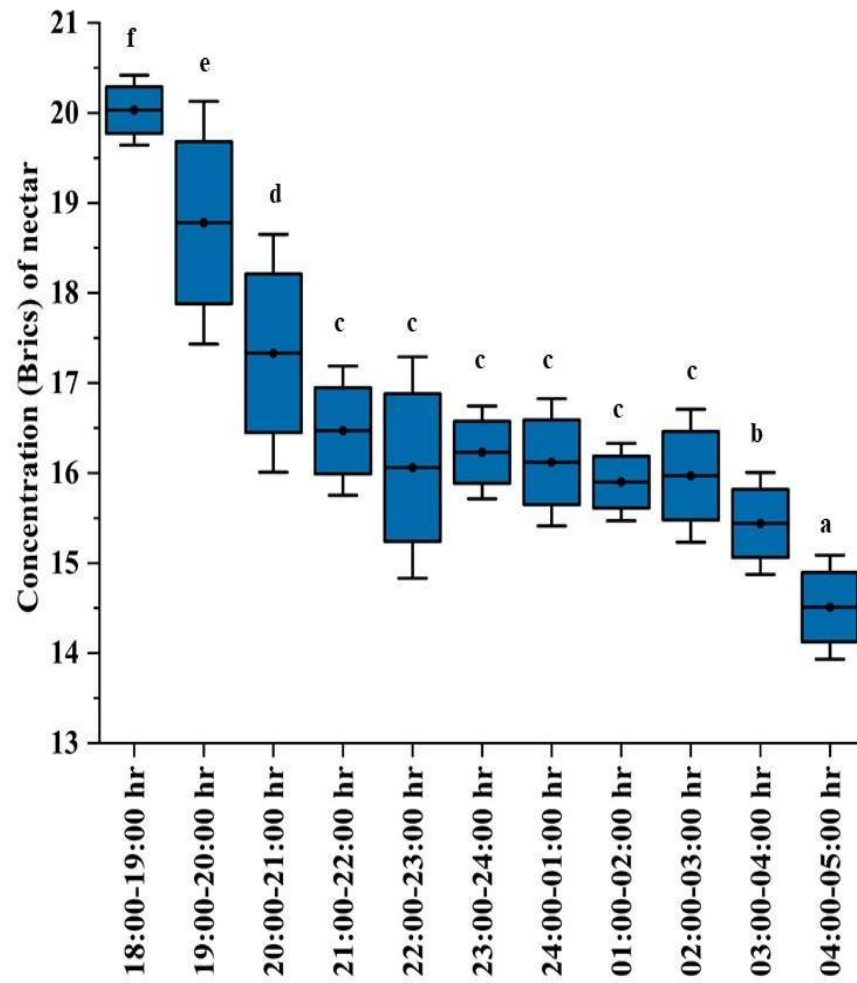


Figure 5.72. Concentration (Brics) of nectar w.r.t. time block

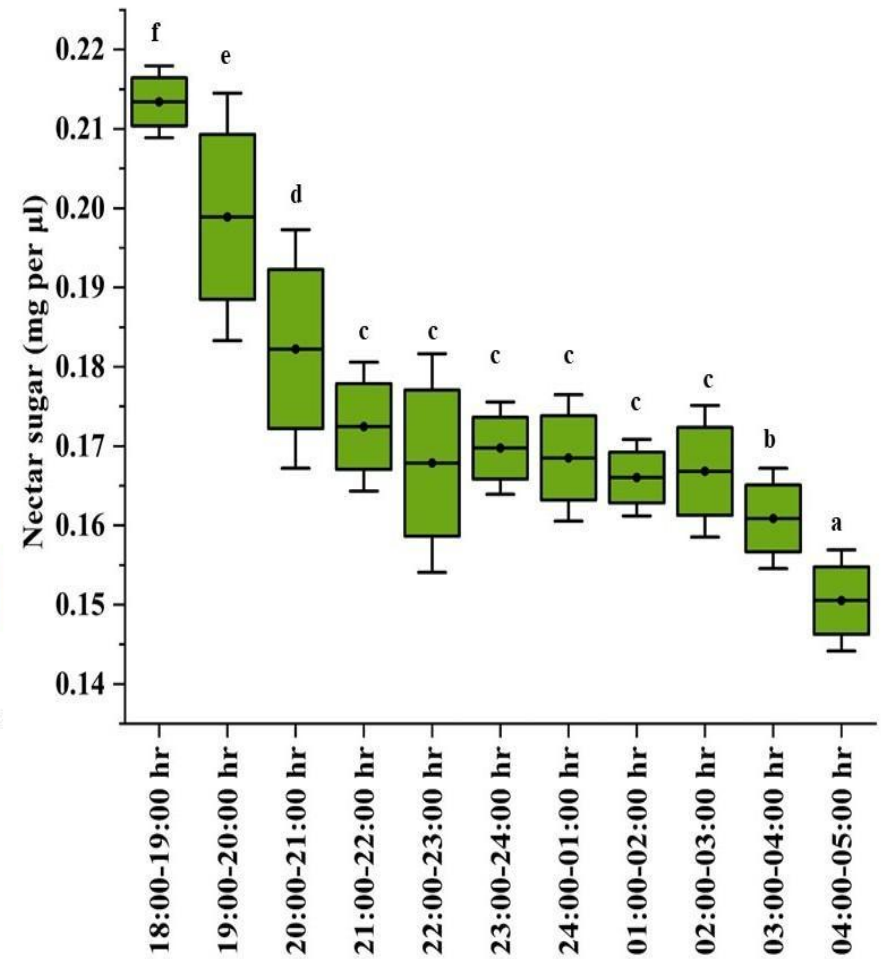


Figure 5.73. Amount of nectar sugar (mg per µl) w.r.t. time block

reaching 16.47 ± 0.48 °Bx between 21:00-22:00 hr and stabilizing at 16.06 ± 0.82 °Bx from 22:00-23:00 hr (Figure 5.72). A slight increase in nectar concentration was observed at 23:00-24:00 hr (16.23 ± 0.34 °Bx), but this was followed by a gradual decline again through the early morning hours, reaching a low of 14.51 ± 0.38 °Bx by 04:00-05:00 hr (Figure 5.72).

These results highlight the nocturnal pattern of nectar secretion, with a distinct peak in the evening followed by a gradual decrease through the night, likely driven by plant physiological rhythms and climatic variables such as temperature and humidity. The relatively low standard deviation values indicate consistent nectar secretion during each time block. The observed decrease in nectar concentration through the night and early morning may be linked to changes in metabolic activity or environmental conditions, such as cooler temperatures or reduced pollinator activity, which could limit nectar secretion. This study offers important insights into the temporal dynamics of nectar availability and its potential effects on plant-pollinator interactions, suggesting that understanding the timing of nectar secretion can help predict pollinator foraging behavior and optimize the management of plant-pollinator relationships.

5.10.2. Amount of nectar sugar collected hourly

The amount of nectar sugar (mg per µl) of *P. timoriana* was measured across hourly intervals to assess the temporal dynamics of nectar composition throughout the evening and early morning. The concentration of nectar sugar was highest during the 18:00-19:00 hr period, with a value of 0.2134 ± 0.0030 mg per µl, suggesting peak nectar production early in the evening (Figure 5.73). The concentration then gradually declined, with a decrease to 0.1989 ± 0.0104 mg per µl by 19:00-20:00 hr and further to 0.1823 ± 0.0100 mg per µl at 20:00-21:00 hr (Figure 5.73). The decrease continued, reaching 0.1725 ± 0.0054 mg per µl between 21:00-22:00 hr, after which nectar sugar concentrations plateaued between 22:00-02:00 hr, fluctuating slightly from 0.1679 ± 0.0092 mg per µl to 0.1668 ± 0.0055 mg per µl. The lowest concentration was observed between the time block 04:00-05:00 hr (0.1505 ± 0.0043 mg per µl), indicating a reduction in nectar sugar during the early morning hours (Figure 5.73).

These findings suggest a clear nocturnal rhythm in nectar sugar concentration, with a peak in the evening followed by a gradual decline overnight. This pattern may reflect the trees's metabolic adjustments in response to factors such as temperature, humidity, or time-dependent resource allocation to pollinator attraction. The stability in nectar sugar levels during the late evening and early night could indicate a strategy to maintain nectar availability for nocturnal pollinators. The observed reduction in nectar sugar towards the morning hours may be attributed to environmental conditions or the depletion of nectar stores. This study offers important insights into the temporal dynamics of nectar production, which has significant implications for pollination ecology, particularly in relation to plant-pollinator interactions and the timing of nectar availability.

5.10.3. Amount of nectar collected

The hourly collection of nectar of *P. timoriana* revealed significant variation in nectar availability, with the highest quantities recorded in the evening hours. The peak of nectar collection occurred between 21:00 and 22:00 hr, where 2.65 ± 0.14 ml of nectar was collected, followed closely by the 20:00-21:00 hr period, yielding 2.57 ± 0.12 ml (Figure 5.74). These results suggest that nectar production is at its highest in the early evening, which may coincide with increased pollinator activity during these hours. The concentration of nectar collected began to decrease progressively after 22:00 hr, with 2.28 ± 0.18 ml collected between 22:00-23:00 hr, and 1.90 ± 0.17 ml between 23:00-24:00 hr (Figure 5.74). By the early hours of the morning, from 01:00-02:00 hr to 04:00-05:00 hr, nectar collection continued to decline, reaching the lowest amount of 0.47 ± 0.14 ml at 04:00-05:00 hr (Figure 5.74).

This progressive reduction in nectar collection aligns with typical patterns observed in tree metabolic activity and the nocturnal cycle of pollinator interactions. The significant decline in nectar availability overnight could be due to factors such as cooler temperatures, reduced pollinator visitation, or lower metabolic processes in plants during the night. These findings underscore the dynamic nature of nectar secretion, with trees optimizing nectar availability during specific periods to enhance

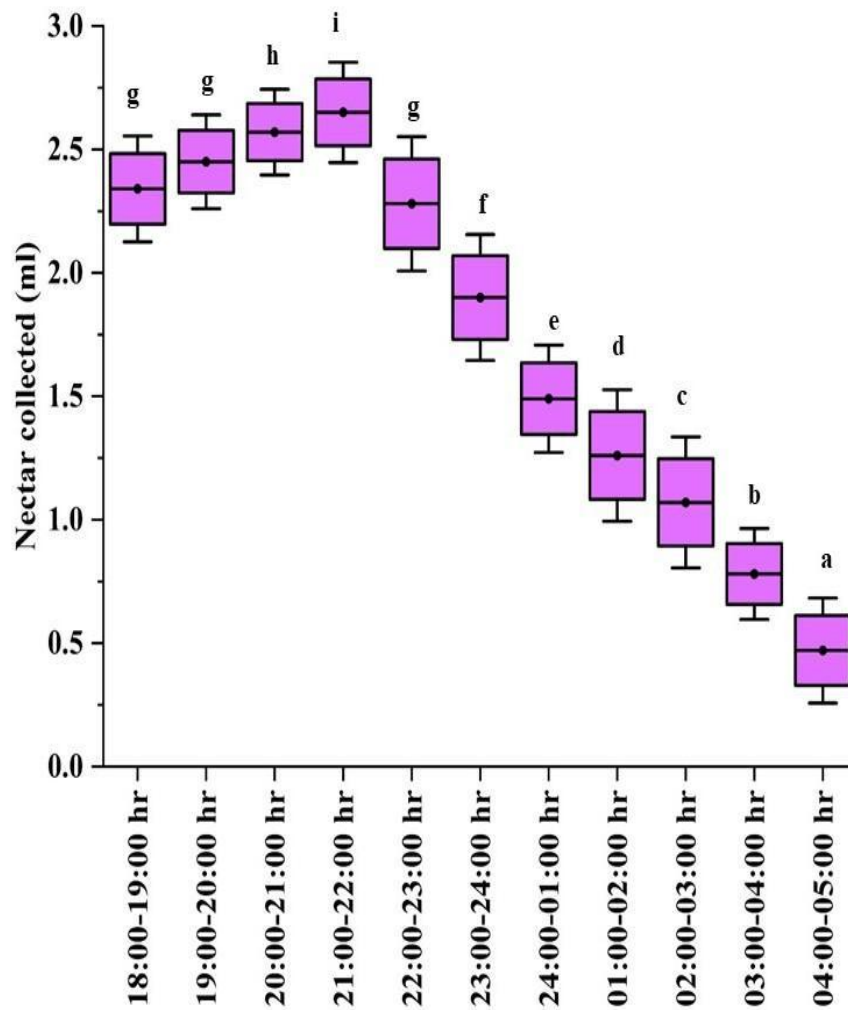


Figure 5.74. Amount of nectar collected (ml) in each time

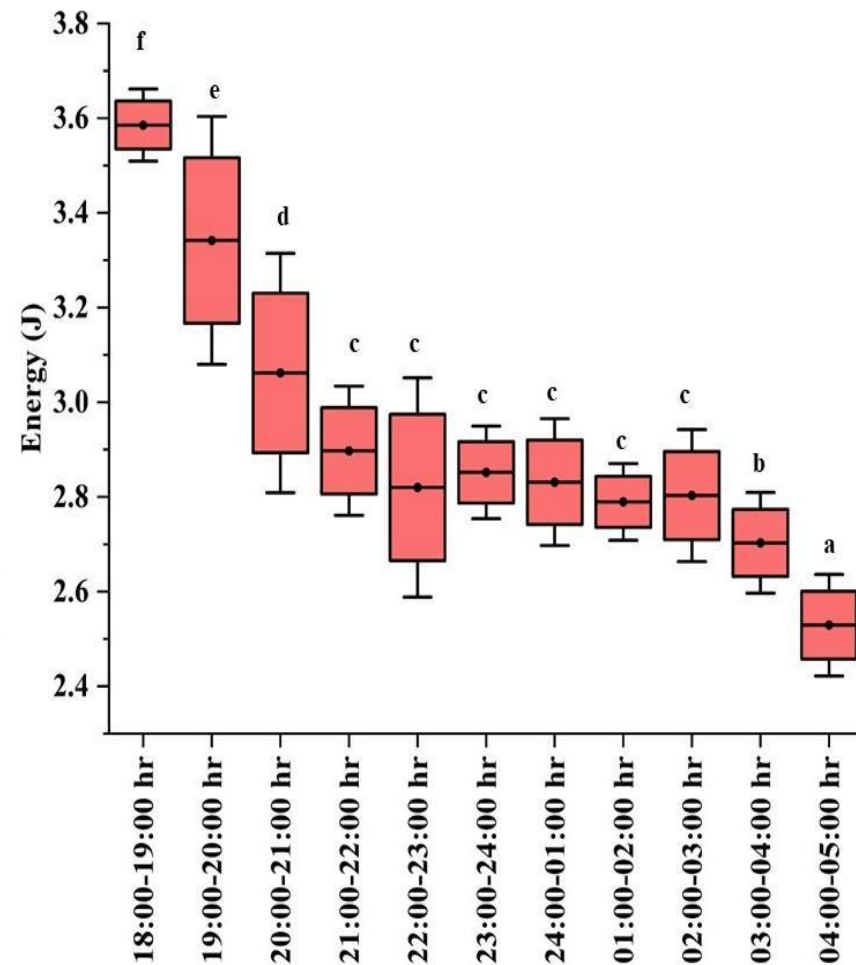


Figure 5.75. Nectar energetics value (J) w.r.t. time block

pollination success. This study provides critical insights into the timing of nectar secretion, offering a deeper understanding of plant-pollinator dynamics and their potential implications for ecological and agricultural practices, especially those related to pollinator-driven crop pollination.

5.10.4. Nectar energetics value

The nectar energetics of *P. timoriana* were measured across several hourly intervals to assess temporal variations in energy content. The highest nectar energetics were recorded during the 18:00-19:00 hr time block, with a value of 3.59 ± 0.05 J, reflecting peak nectar energy concentration at the start of the evening (Figure 5.75). A decline in nectar energetics was observed as the night progressed, with a decrease to 3.34 ± 0.17 J between 19:00-20:00 hr, followed by further reductions to 3.06 ± 0.17 J at 20:00-21:00 hr, and 2.90 ± 0.09 J during 21:00-22:00 hr (Figure 5.75). After 22:00 hr, the nectar energetics continued to decline, reaching 2.82 ± 0.15 J by 22:00-23:00 hr and 2.85 ± 0.07 J between 23:00-24:00 hr. From midnight onwards, the decrease persisted, with nectar energetics reaching 2.83 ± 0.09 J during 24:00-01:00 hr, 2.79 ± 0.05 J during 01:00-02:00 hr, and 2.80 ± 0.09 J at 02:00-03:00 hr. The lowest value was recorded between 04:00-05:00 hr with the final reading of 2.53 ± 0.07 , marking the nadir of nectar energetics for the measurement period (Figure 5.75).

These results indicate a distinct nocturnal pattern in nectar energetics, with a peak in the early evening followed by a consistent decrease through the night and early morning. This decline in nectar energetics could be attributed to several factors, such as reduced tree metabolic activity and lower temperatures during the night, both of which may limit nectar secretion and energy content. The consistency of measurements, as indicated by the low standard deviations within each time block, suggests reliable data collection across the measured intervals. These findings are crucial for understanding the energy dynamics of nectar production and have implications for optimizing the timing of pollinator interactions. The observed pattern also provides insights into how nectar energy content fluctuates over time, which can influence the behavior of pollinators and their efficiency in transferring pollen.

5.10.5. Amount of nectar collected (ml) daily per inflorescence

The average amount of nectar collected daily per inflorescence of *P. timoriana* was found to be 14.69 ml, with a standard deviation of 0.88 (Figure 5.76.). This indicates a relatively consistent quantity of nectar produced by the inflorescences on a daily basis, with minimal variation across the measured period. The mean value suggests that, on average, each inflorescence contributes a moderate amount of nectar, likely playing a crucial role in attracting pollinators and ensuring successful pollination. The low standard deviation further emphasizes the stability of nectar secretion, which could be attributed to consistent environmental conditions or steady plant metabolic processes that regulate nectar secretion. This study offers important insights into the dynamics of nectar availability, which is fundamental for understanding plant-pollinator interactions and the ecological role of nectar in plant reproduction. Further studies could explore the environmental or physiological factors that influence this consistent nectar production and its impact on pollinator behavior and ecosystem functioning.

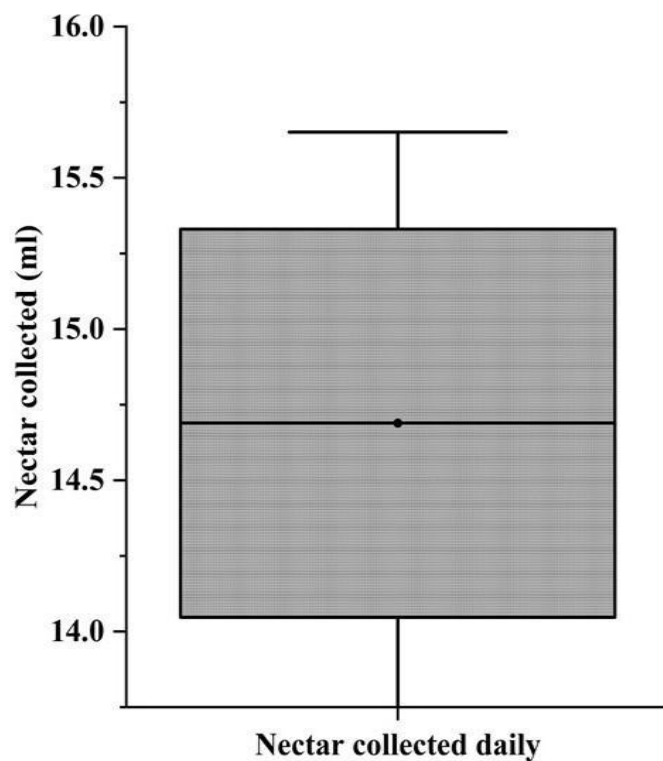


Figure 5.76. Amount of nectar collected (ml) daily per inflorescence.

5.10.6. Analysis of sugars in nectar using HPLC

The sugar profile of *P. timoriana* nectar was analyzed, revealing the presence of three primary sugars: glucose, fructose, and sucrose. Among these, sucrose was found to be the most abundant, with a concentration of 889.69 ppm, followed by fructose at 363.11 ppm, and glucose at 320.21 ppm (Table 5.18.). The higher concentration of sucrose suggests that it may play a critical role in the energy provision of the nectar, while the relatively lower concentrations of glucose and fructose indicate their contribution to the overall sugar composition. The composition of these sugars in *P. timoriana* nectar could have implications for the plant's interaction with pollinators, as these sugars are known to influence nectar preferences and foraging behavior in a variety of pollinator species. The dominance of sucrose may be indicative of the nectar's suitability for a wide range of pollinators, as sucrose is a preferred sugar in many bee species. This study offers important insights into the deeper understanding of the biochemical characteristics of *P. timoriana* nectar and its potential ecological significance in pollinator attraction.

Table 5.18. Types of sugars detected from the nectar of *P. timoriana*

Sl. No.	Compound	Concentration (ppm)
1.	Glucose	320.21
2.	Fructose	363.11
3.	Sucrose	889.69

5.10.7. Analysis of amino acids in nectar using HPLC

The amino acid composition of the nectar from *P. timoriana* was comprehensively analyzed, revealing a diverse profile of amino acids present at varying concentrations. Aspartic acid, the most prevalent amino acid in the nectar, was found at a concentration of 3.891 ppm, with a retention time of 3.150 minutes, corresponding to peak area and height measurements of 138,519 and 20,287, respectively (Table 5.19. and Figure 5.77). Glutamic acid was also detected in significant quantities (2.746 ppm), with a retention time of 3.967 min. and peak area and height values of 95,496 and 15,452, respectively (Table 5.19. and Figure 5.77). Asparagine, another prominent amino acid, had a concentration of 3.592 ppm, with an exceptional peak area of 569,234 and a

Table 5.19. List of amino acids detected from the nectar of *P. timoriana*

Sl.no.	Amino acids	Retention time (min.)	Concentration (ppm)	Area	Height
1.	Aspartic acid	3.150	3.891	138519	20287
2.	Glutamic acid	3.967	2.746	95496	15452
3.	Asparagine	6.942	3.592	569234	67696
4.	Serine	8.000	0.520	134390	13231
5.	Glutamine	9.358	5.640	1116054	116447
6.	Histidine	10.583	0.302	78032	6870
7.	Glycine	11.419	0.049	57987	6236
8.	Threonine	11.858	0.216	78680	6813
9.	Arginine	14.042	0.061	19977	1949
10.	Alanine	15.975	0.251	87185	7659
11.	Tyrosine	21.075	0.021	7592	675
12.	Cystine	27.783	1.601	81956	4415
13.	Valine	28.483	0.613	77635	6331
14.	Tryptophan	33.267	0.017	3682	355
15.	Phenylalanine	34.708	0.015	2009	266
16.	Isoleucine	35.400	0.305	57106	4309
17.	Leucine	38.175	0.535	76750	3365
18.	Lysine	45.967	0.046	7901	549

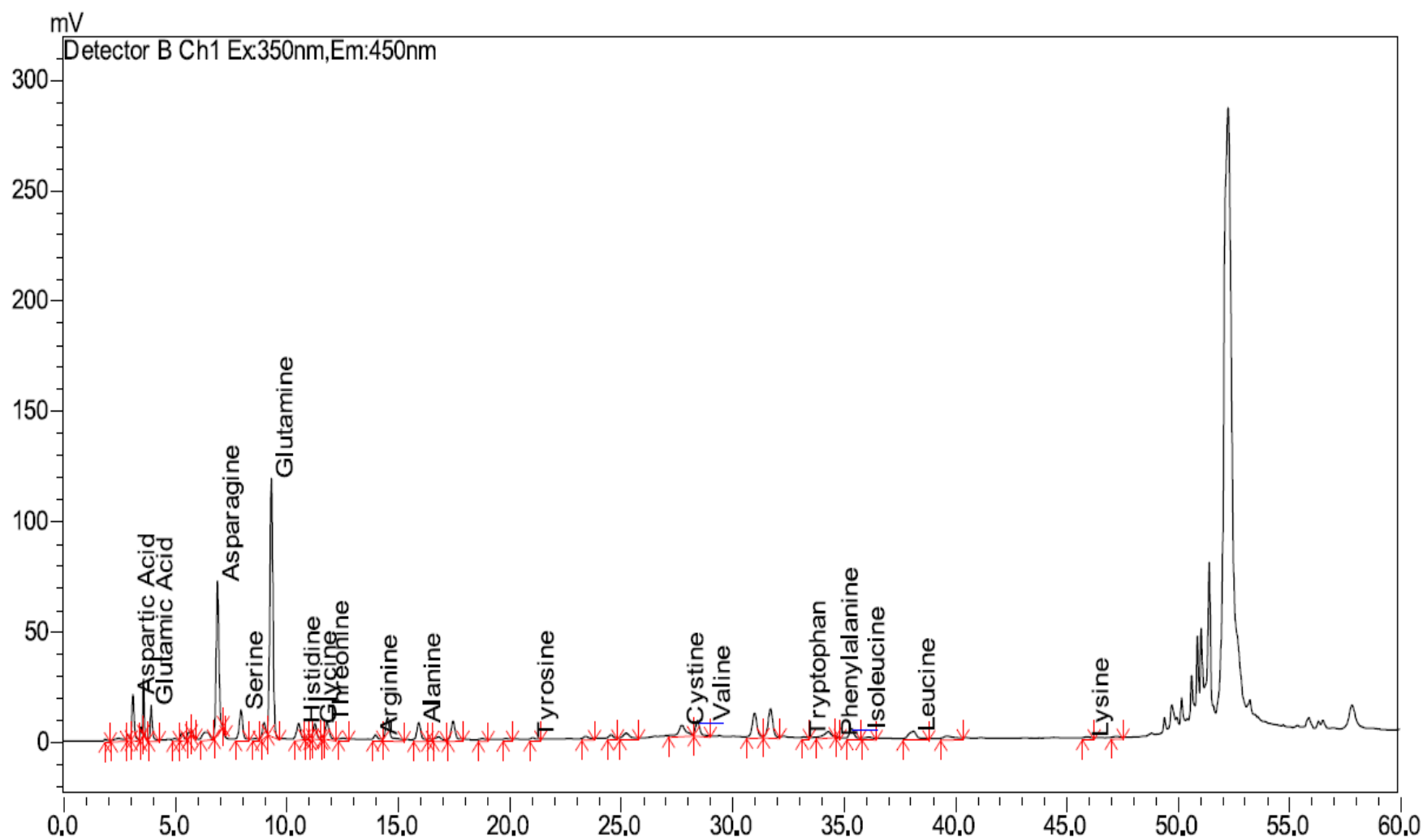


Figure 5.77. Chromatogram of amino acids in nectar sample.

height of 67,696 at a retention time of 6.942 minutes. Glutamine, exhibiting the highest concentration at 5.640 ppm, was identified with a retention time of 9.358 min. and a peak area of 1,116,054 and a height of 116,447 (Table 5.19. and Figure 5.77).

Other amino acids present in the nectar, albeit in lower concentrations, included serine (0.520 ppm), histidine (0.302 ppm), glycine (0.049 ppm), and threonine (0.216 ppm), with corresponding retention times of 8.000, 10.583, 11.419, and 11.858 minutes. Arginine was found at a concentration of 0.061 ppm, with a retention time of 14.042 minutes, while alanine, tyrosine, and cystine were present in trace amounts, with concentrations of 0.251 ppm, 0.021 ppm, and 1.601 ppm, respectively (Table 5.19. and Figure 5.77). Their respective retention times were 15.975 minutes for alanine, 21.075 minutes for tyrosine, and 27.783 minutes for cystine. Additionally, valine (0.613 ppm), tryptophan (0.017 ppm), phenylalanine (0.015 ppm), isoleucine (0.305 ppm), leucine (0.535 ppm), and lysine (0.046 ppm) were detected, with retention times ranging from 28.483 minutes to 45.967 minutes (Table 5.19. and Figure 5.77).

The presence of these amino acids in varying concentrations indicates a complex biochemical profile of the nectar of *P. timoriana*. The diversity of amino acids, particularly the significant presence of glutamine, asparagine, and aspartic acid, may contribute to the nutritional and biochemical properties of the nectar, influencing its role in plant-pollinator interactions. This study offers important insights into the metabolic composition of *P. timoriana* nectar and its potential ecological functions.

5.10.8. Spearman's rank correlation analysis between different nectar properties and environmental parameters studied.

Spearman's rank correlation analysis was performed to assess the relationships between nectar properties, specifically nectar per hour, concentration of nectar, and energetics value of nectar and various environmental parameters, as well as the daily nectar collection in relation to these parameters. The results presented in Table 5.20. demonstrate strong negative correlations between time (T) and all nectar properties, with r_s values of -0.890^{**} ($p < 0.01$) for nectar per hour, -0.850^{**} ($p < 0.01$) for concentration of nectar, and -0.890^{**} ($p < 0.01$) for energetics value, indicating that

Table 5.20. Spearman's rank correlation analysis between different nectar properties and environmental parameters studied.

	Nectar per hr		Concentration of nectar		Energetics value of nectar (J)	
	r_s	p	r_s	p	r_s	p
T	-0.890**	0.000	-0.850**	0.000	-0.890**	0.000
TM	0.614**	0.000	0.589**	0.000	0.614**	0.000
TDEW	0.655**	0.000	0.638**	0.000	0.655**	0.000
TWET	0.644**	0.000	0.621**	0.000	0.644**	0.000
QV	0.655**	0.000	0.638**	0.000	0.655**	0.000
RH	-0.183	0.055	-0.179	0.061	-0.183	0.055
PR	-0.012	0.902	0.094	0.330	-0.012	0.902
PS	0.208*	0.029	-0.126	0.191	0.208*	0.029
WS	0.102	0.290	-0.005	0.957	0.102	0.290
Nectar per hr	1	-	0.682**	0.000	1.000**	-
Concentration of nectar	0.682**	0.000	1	-	0.682**	0.000
Energetics value of nectar (J)	1.000**	-	0.682**	0.000	1.000**	-
** Correlation is significant at the 0.01 level (2-tailed).						
* Correlation is significant at the 0.05 level (2-tailed).						

Table 5.21. Spearman's rank correlation analysis between nectar collected daily and environmental parameters studied.

	Nectar collected daily	
	r_s	p
T	-0.113	0.264
TM	-0.010	0.923
TDEW	0.004	0.970
TWET	0.030	0.764
TMMA	-0.033	0.744
TMMI	0.140	0.165
QV	0.034	0.738
RH	0.020	0.845
PR	0.037	0.711
PS	0.036	0.722
WS	-0.122	0.228
WSMA	-0.220*	0.228
SSW	0.222*	0.027
RZSW	0.227*	0.023

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

as time progresses, nectar production and its associated properties tend to decrease. In contrast, temperature at 2 meters (TM), dew/frost point at 2 meters (TDEW), wet bulb temperature at 2 meters (TWET), and specific humidity at 2 meters (QV) were all positively correlated with nectar properties, with r_s values ranging from 0.589 to 0.655 ($p < 0.01$), suggesting that warmer and more humid conditions favor increased nectar production. Relative humidity (RH), precipitation (PR), and wind speed at 2 meters (WS) showed minimal or no significant correlations with nectar properties ($p > 0.05$), indicating a weaker influence of these variables on nectar dynamics. Table 5.21. focused on daily nectar collection, revealing minimal significant correlations between environmental parameters and daily nectar yield, except for soil moisture-related variables. Specifically, surface soil wetness (SSW) and root zone soil wetness (RZSW) were both positively correlated with daily nectar collection ($r_s = 0.222^*$, $p < 0.05$ and $r_s = 0.227^*$, $p < 0.05$, respectively), suggesting that increased soil moisture may enhance nectar collection. Additionally, maximum wind speed at 2 meters (WSMA) displayed a marginally significant negative correlation ($r_s = -0.220^*$, $p < 0.05$), indicating that stronger wind speeds may negatively impact nectar collection. Overall, the analysis highlights the complex interplay between environmental conditions and

nectar dynamics, with temperature, humidity, and soil moisture emerging as key factors influencing both nectar production and collection. These findings underscore the importance of considering a range of environmental variables when studying nectar ecology, as they collectively shape the quantity and quality of nectar available.

5.11. *In vitro* pollen germination

5.11.1. Effect of distilled water and sucrose on *in vitro* pollen germination w.r.t. time block.

The impact of distilled water and varying sucrose concentrations on *in vitro* pollen germination was evaluated using sucrose concentrations of 5%, 10%, 15%, and 20%, in addition to distilled water. In the distilled water treatment, no pollen germination was observed at 24 hrs (0.00%), with a slight increase to 1.38% at 48 hrs, followed by a small decrease to 1.02% at 72 hrs (Figure 5.78.). The sucrose treatments exhibited more significant effects on pollen germination (Figure 5.79.). At 5% sucrose, no germination was recorded at 24 hrs, but by 48 hrs, germination reached 4.10%, only to decline to 1.28% at 72 hrs (Figure 5.78.). In the 10% sucrose treatment, pollen germination began at 3.45% at 24 hrs, decreased to 2.73% at 48 hrs, and further declined to 2.01% at 72 hrs (Figure 5.78.). The 15% sucrose solution showed the highest germination at 24 hrs (6.39%), decreased to 5.53% at 48 hrs, and further dropped to 2.92% at 72 hrs (Figure 5.78.). Similarly, the 20% sucrose treatment began with 5.64% germination at 24 hrs, decreased to 3.00% at 48 hrs, and further reduced to 1.02% at 72 hrs (Figure 5.78.). Statistical analysis confirmed a significant difference in pollen germination between the 24 hrs, 48 hrs, and 72 hrs time points for all treatments at the 0.01 level. These findings suggest that sucrose concentrations, especially at 15% and 20%, are more effective in promoting pollen germination compared to distilled water, although germination decreases with time, particularly at the 72 hrs mark. This study highlights the critical role of sucrose concentration and incubation duration in optimizing *in vitro* pollen germination.

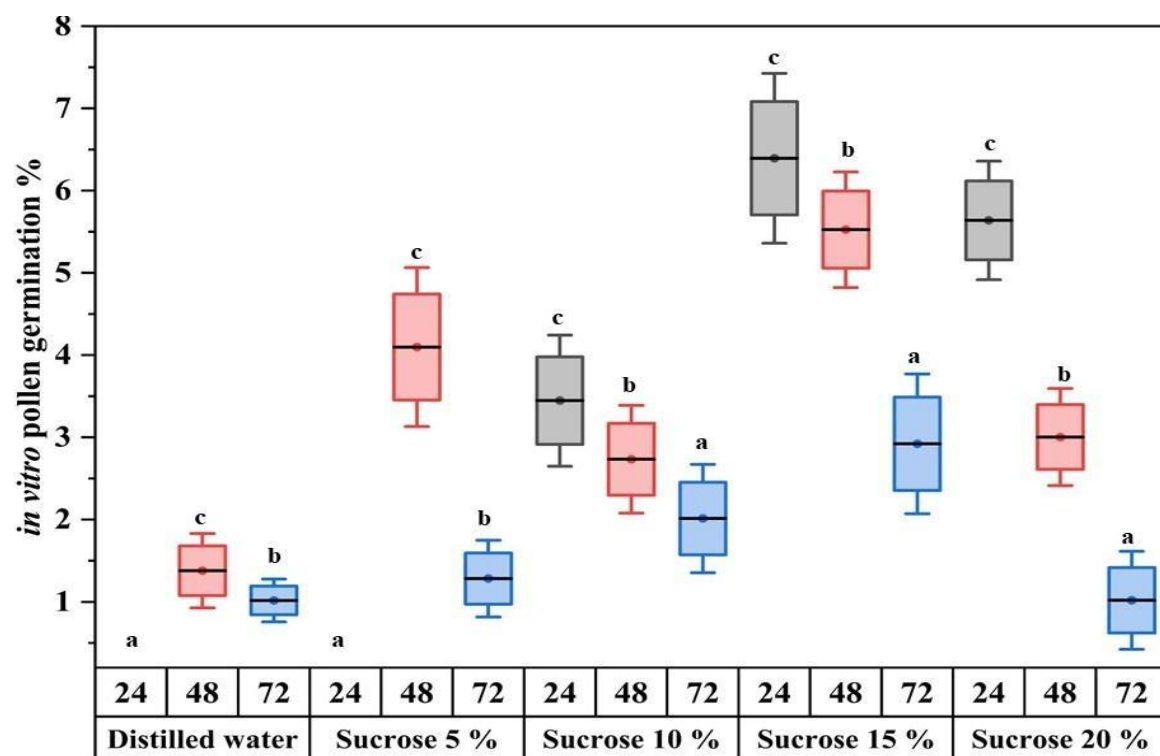


Figure 5.78. Effect of distilled water and sucrose on *in vitro* pollen germination w.r.t. time block.

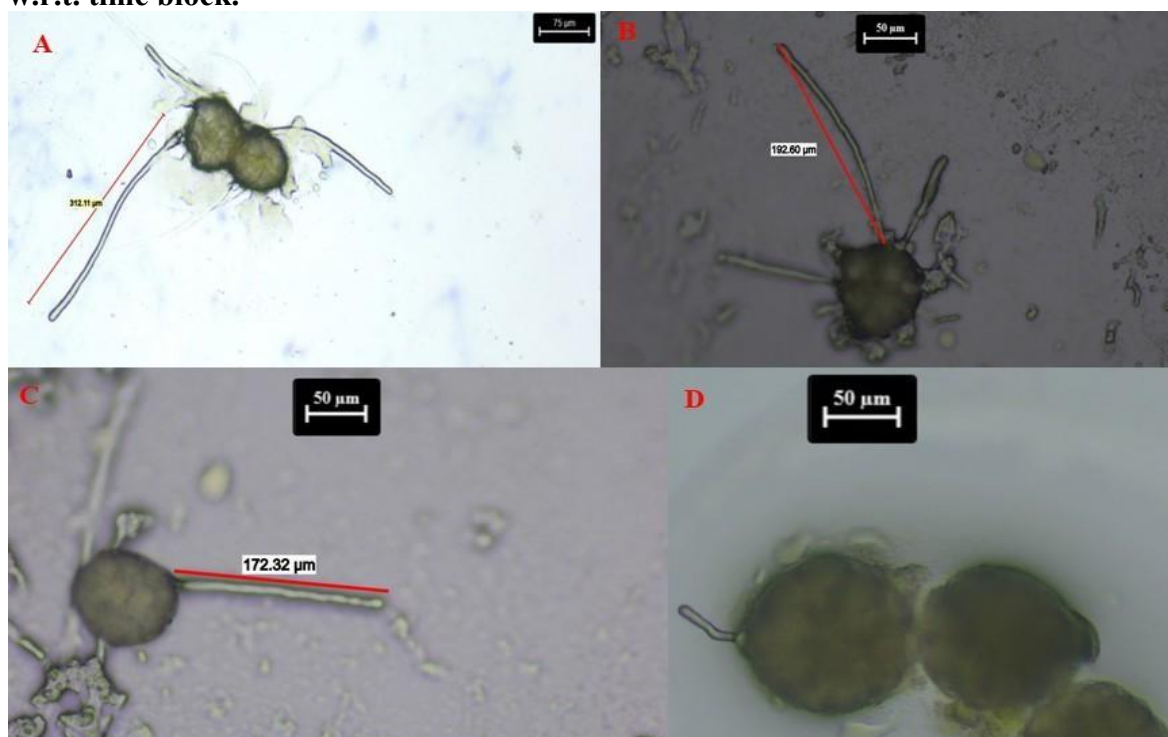


Figure 5.79. *In vitro* pollen germination of *P. timoriana* pollen grains with extension of pollen tube

5.11.2. Effect of time on *in vitro* pollen germination w.r.t. distilled water and sucrose.

The effect of time on *in vitro* pollen germination in relation to distilled water and sucrose concentrations of 5%, 10%, 15%, and 20% was evaluated across three time intervals: 24 hours, 48 hours, and 72 hours. At the 24-hour time point, no pollen germination was observed in the distilled water and sucrose 5% treatments, both showing 0.00% germination (Figure 5.80.). In contrast, the sucrose solutions at 10%, 15%, and 20% concentrations demonstrated significantly higher germination with values of 3.45%, 6.39%, and 5.64%, respectively (Figure 5.80.). Statistical analysis revealed a significant difference between distilled water and sucrose 5% when compared to sucrose 10%, 15%, and 20% at the 0.01 level; however, there was no significant difference between distilled water and sucrose 5%. At 48 hours, all treatments showed germination with distilled water exhibiting 1.38%, sucrose 5% showing 4.10%, sucrose 10% at 2.73%, sucrose 15% at 5.53%, and sucrose 20% at 3.00% (Figure 5.80.). The statistical comparison indicated a significant difference between sucrose 10% and sucrose 20% compared to distilled water, sucrose 5%, and sucrose 15%, while no significant difference was found between sucrose 10% and sucrose 20% (Figure 5.80.). At 72 hours, a decrease in germination was observed across all treatments, with distilled water and sucrose 5% showing 1.02% and 1.28%, respectively, while sucrose 10%, 15%, and 20% exhibited germination percentages of 2.01%, 2.92%, and 1.02% (Figure 5.80.). Statistical analysis at this time point showed no significant differences between distilled water, sucrose 5%, and sucrose 20%, but significant differences were found between sucrose 10% and sucrose 15% compared to the other treatments. These findings underscore the importance of sucrose concentration and time duration in enhancing pollen germination *in vitro*, with sucrose 15% demonstrating the highest germination at 24 hrs, and a marked decline in germination over time, particularly at 72 hrs.

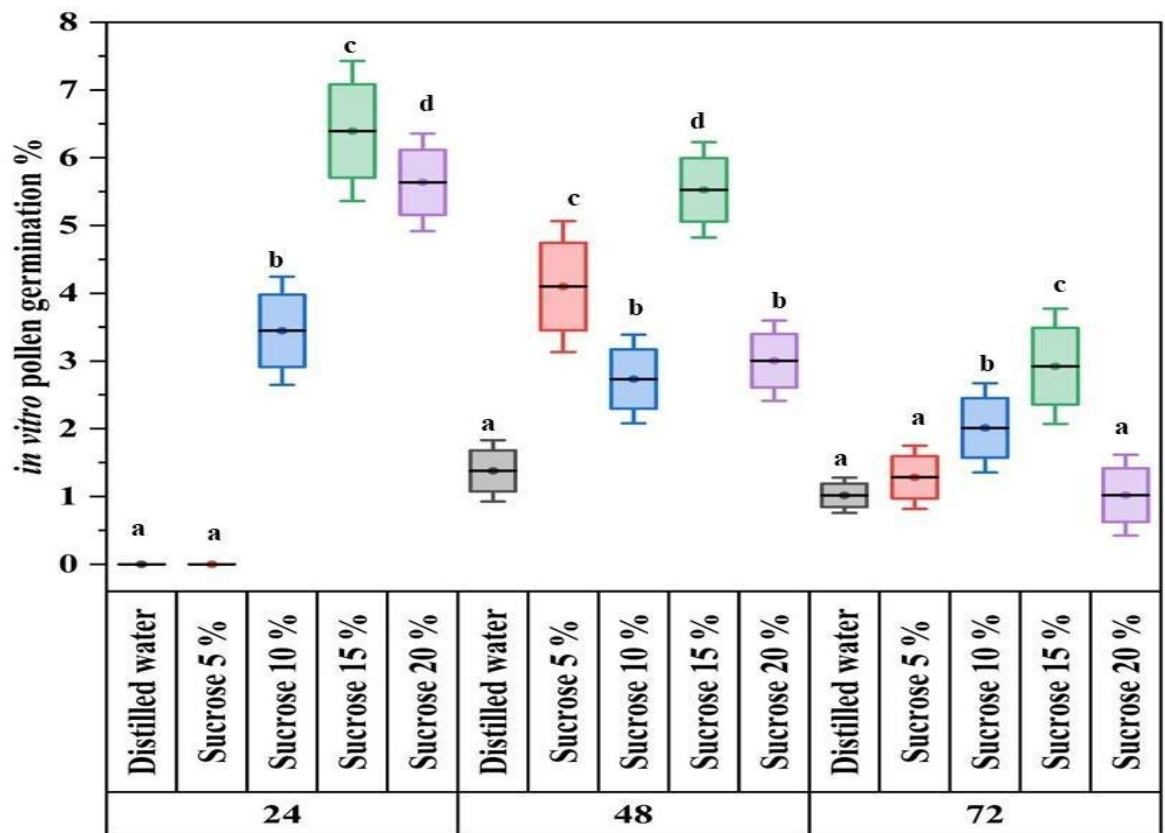


Figure 5.80. Effect of time on *in vitro* pollen germination w.r.t. distilled water and sucrose.

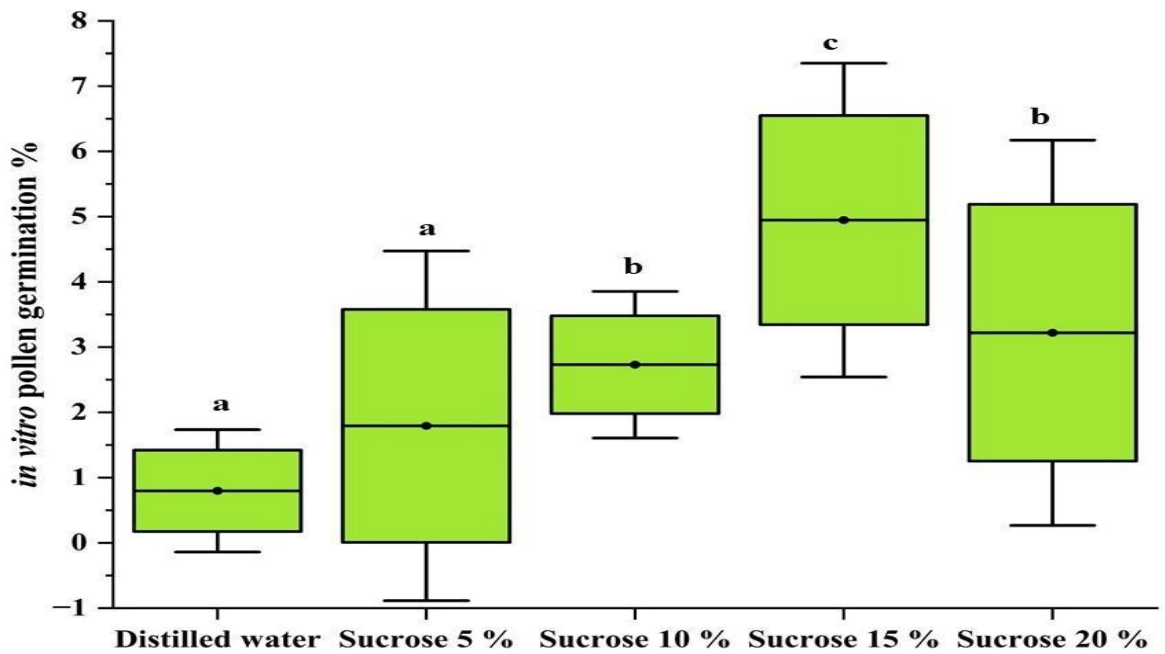


Figure 5.81. Effect of distilled water and sucrose on *in vitro* pollen germination.

5.11.3. Effect of distilled water and sucrose on *in vitro* pollen germination.

The impact of distilled water and various sucrose concentrations (5%, 10%, 15%, and 20%) on *in vitro* pollen germination was assessed. The results demonstrated that distilled water resulted in a relatively low pollen germination rate of 0.80% (Figure 5.81.). In comparison, sucrose treatments yielded higher pollen germination percentages, with sucrose 5% showing a germination rate of 1.79 %, sucrose 10% at 2.73%, sucrose 15% at 4.95%, and sucrose 20% at 3.22% (Figure 5.81.). Statistical analysis revealed no significant difference between distilled water and 5% sucrose, while significant differences were observed between distilled water and the other sucrose concentrations at the 0.05 level. Furthermore, there was a significant difference between sucrose 10%, sucrose 15%, and sucrose 20%, suggesting that higher sucrose concentrations more effectively promoted pollen germination. These findings underscore the importance of sucrose concentration in optimizing *in vitro* pollen germination, with sucrose 15% showing the highest germination rate, followed by sucrose 20% and sucrose 10%.

5.11.4. Effect of different conc. of IAA on *in vitro* pollen germination w.r.t. time.

The effect of different concentrations of indole-3-acetic acid (IAA) on *in vitro* pollen germination was evaluated over different concentrations of IAA: IAA 10 ppm, IAA 20 ppm, IAA 50 ppm and IAA 100 ppm. For IAA 10 ppm, the germination % was $3.97 \pm 0.56\%$ at 24 hrs. These values significantly decreased over time reaching $2.98 \pm 0.51\%$ at 48 hrs and $0.79 \pm 0.24\%$ at 72 hrs (Figure 5.82.). Similarly, IAA 20 ppm exhibited a decrease from $8.15 \pm 0.43\%$ at 24 hrs to $2.72 \pm 0.30\%$ at 48 hrs, and $1.06 \pm 0.41\%$ at 72 hrs (Figure 5.82.). For IAA 50 ppm, germination dropped from $17.98 \pm 0.65\%$ at 24 hrs to $3.65 \pm 0.36\%$ at 48 hrs and $1.43 \pm 0.27\%$ at 72 hrs (Figure 5.82.). Lastly, IAA 100 ppm showed a decrease from $15.51 \pm 0.93\%$ at 24 hrs to $3.51 \pm 0.49\%$ at 48 hrs and $1.66 \pm 0.42\%$ at 72 hrs (Figure 5.82.). Statistical analysis revealed that in all treatments, there was a significant difference between the germination percentages at 24 hrs, 48 hrs, and 72 hrs at the 0.01 level. The highest germination rates were observed at 24 hrs for all concentrations, with a notable reduction over time. These results highlight the significant impact of both the IAA concentration and the duration

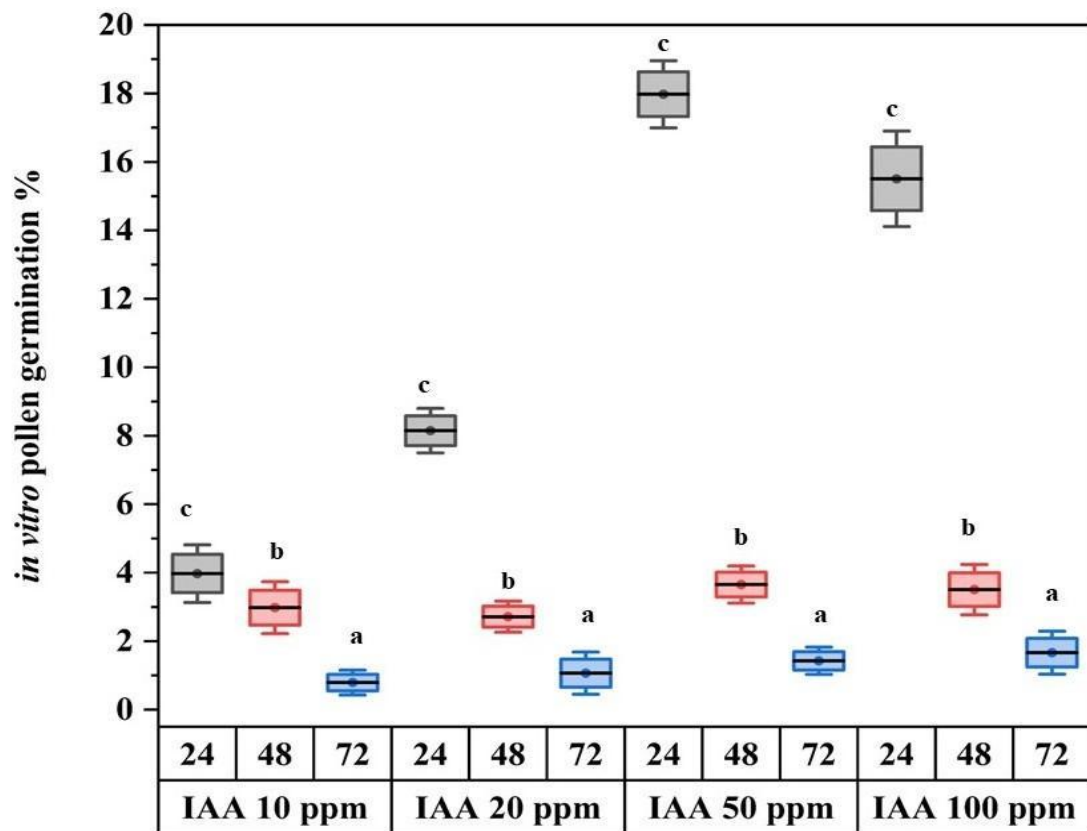


Figure 5.82. Effect of diff. conc. of IAA on *in vitro* pollen germination w.r.t. time.

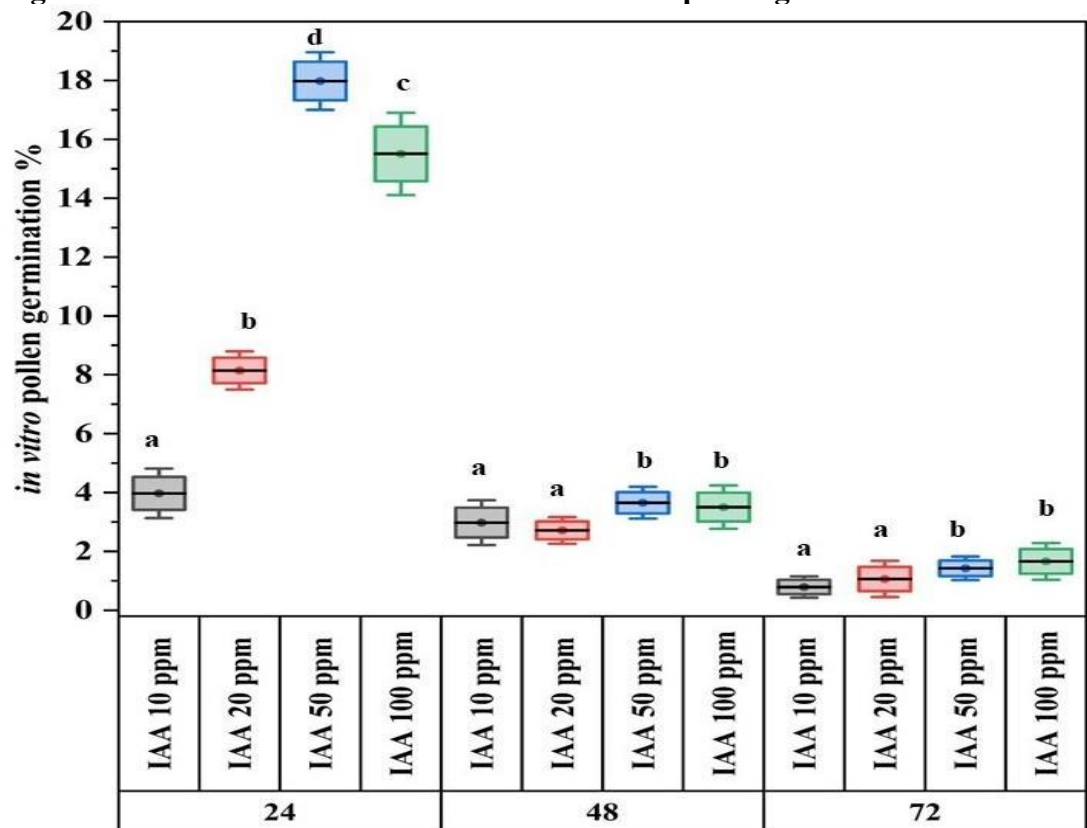


Figure 5.83. Effect of time on *in vitro* pollen germination w.r.t. diff. conc. of IAA.

of exposure on pollen germination, emphasizing that the optimal pollen germination occurs within the first 24 hours of exposure to IAA.

5.11.5. Effect of time on *in vitro* pollen germination w.r.t. different concentration of IAA.

The influence of time on *in vitro* pollen germination w.r.t. different conc. of indole-3-acetic acid (IAA) was examined over three time intervals: 24 hrs, 48 hrs, and 72 hrs. At the 24 hrs interval, significant differences in pollen germination were observed across the various concentrations of IAA. Germination percentages were $3.97 \pm 0.56\%$ for IAA 10 ppm, $8.15 \pm 0.43\%$ for IAA 20 ppm, $17.98 \pm 0.65\%$ for IAA 50 ppm, and $15.51 \pm 0.93\%$ for IAA 100 ppm (Figure 5.83.). Statistical analysis revealed that all concentrations differed significantly at the 0.01 level, with IAA 50 ppm exhibiting the highest germination rate, followed by IAA 100 ppm, IAA 20 ppm, and IAA 10 ppm. At 48 hrs, the germination rates were $2.98 \pm 0.51\%$ for IAA 10 ppm, $2.72 \pm 0.30\%$ for IAA 20 ppm, $3.65 \pm 0.36\%$ for IAA 50 ppm, and $3.51 \pm 0.49\%$ for IAA 100 ppm (Figure 5.83.). Significant differences were found between IAA 10 ppm and IAA 20 ppm compared to IAA 50 ppm and IAA 100 ppm, although no significant differences were observed between IAA 10 ppm and IAA 20 ppm, nor between IAA 50 ppm and IAA 100 ppm. At 72 hrs, pollen germination was observed at $0.79 \pm 0.24\%$ for IAA 10 ppm, $1.06 \pm 0.41\%$ for IAA 20 ppm, $1.43 \pm 0.27\%$ for IAA 50 ppm, and $1.66 \pm 0.42\%$ for IAA 100 ppm (Figure 5.83.). The statistical analysis revealed significant differences between IAA 10 ppm and IAA 20 ppm, compared to IAA 50 ppm and IAA 100 ppm, while no significant differences were found between IAA 10 ppm and IAA 20 ppm or between IAA 50 ppm and IAA 100 ppm. These results indicate that IAA concentration plays a critical role in promoting pollen germination, with higher concentrations yielding better results, particularly at earlier time points. However, the effect diminishes over time, highlighting the importance of timing and concentration in optimizing *in vitro* pollen germination for research and agricultural applications.

5.11.6. Effect of different conc. of IBA on *in vitro* pollen germination w.r.t. time.

The effect of varying concentrations of indole-3-butyric acid (IBA) on *in vitro* pollen germination was examined across different concentrations of IBA: IBA 10 ppm, IBA 20 ppm, IBA 50 ppm, and IBA 100 ppm. For IBA 10 ppm, the initial germination percentage was $6.97 \pm 0.75\%$. This value significantly decreased over time, reaching $1.80 \pm 0.52\%$ at 48 hrs and $1.15 \pm 0.17\%$ at 72 hrs (Figure 5.84.). Similarly, IBA 20 ppm exhibited a decrease from $6.39 \pm 0.72\%$ at 24 hrs to $3.37 \pm 0.60\%$ at 48 hrs, and $1.23 \pm 0.32\%$ at 72 hrs (Figure 5.84.). For IBA 50 ppm, the germination percentage dropped from $17.90 \pm 1.01\%$ at 24 hrs to $7.68 \pm 0.71\%$ at 48 hrs and $5.42 \pm 0.78\%$ at 72 hrs (Figure 5.84.). Lastly, IBA 100 ppm showed a decrease from $29.60 \pm 0.93\%$ at 24 hrs to $7.93 \pm 0.77\%$ at 48 hrs and $2.96 \pm 0.82\%$ at 72 hrs (Figure 5.84.). Statistical analysis revealed that in all treatments, there was a significant difference in germination percentages between 24 hrs, 48 hrs, and 72 hrs at the 0.01 level. The highest germination rates were observed at 24 hrs for all concentrations, with a notable decline as time progressed. These results highlight the significant role of IBA concentration in pollen germination, with higher concentrations leading to greater germination rates, especially at the 24-hour interval. However, the effectiveness of IBA decreased over time, indicating that its impact on pollen germination is most pronounced during the initial 24 hrs.

5.11.7. Effect of time on *in vitro* pollen germination w.r.t. different concentration of IBA.

The influence of time on *in vitro* pollen germination w.r.t. different concentrations of indole-3-butyric acid (IBA) was assessed across three time intervals: 24 hrs, 48 hrs, and 72 hrs. At 24 hours, the pollen germination percentages for IBA 10 ppm, IBA 20 ppm, IBA 50 ppm, and IBA 100 ppm were $6.97 \pm 0.75\%$, $6.39 \pm 0.72\%$, $17.90 \pm 1.01\%$, and $29.60 \pm 0.93\%$, respectively. Statistical analysis revealed significant differences between IBA 10 ppm and IBA 20 ppm with IBA 50 ppm and IBA 100 ppm at the 0.01 level, but no significant difference was observed between IBA 10 ppm and IBA 20 ppm (Figure 5.85.). At 48 hours, germination percentages were $1.80 \pm 0.52\%$ for IBA 10 ppm, $3.37 \pm 0.60\%$ for IBA 20 ppm, $7.68 \pm 0.71\%$ for IBA 50 ppm, and $7.93 \pm$

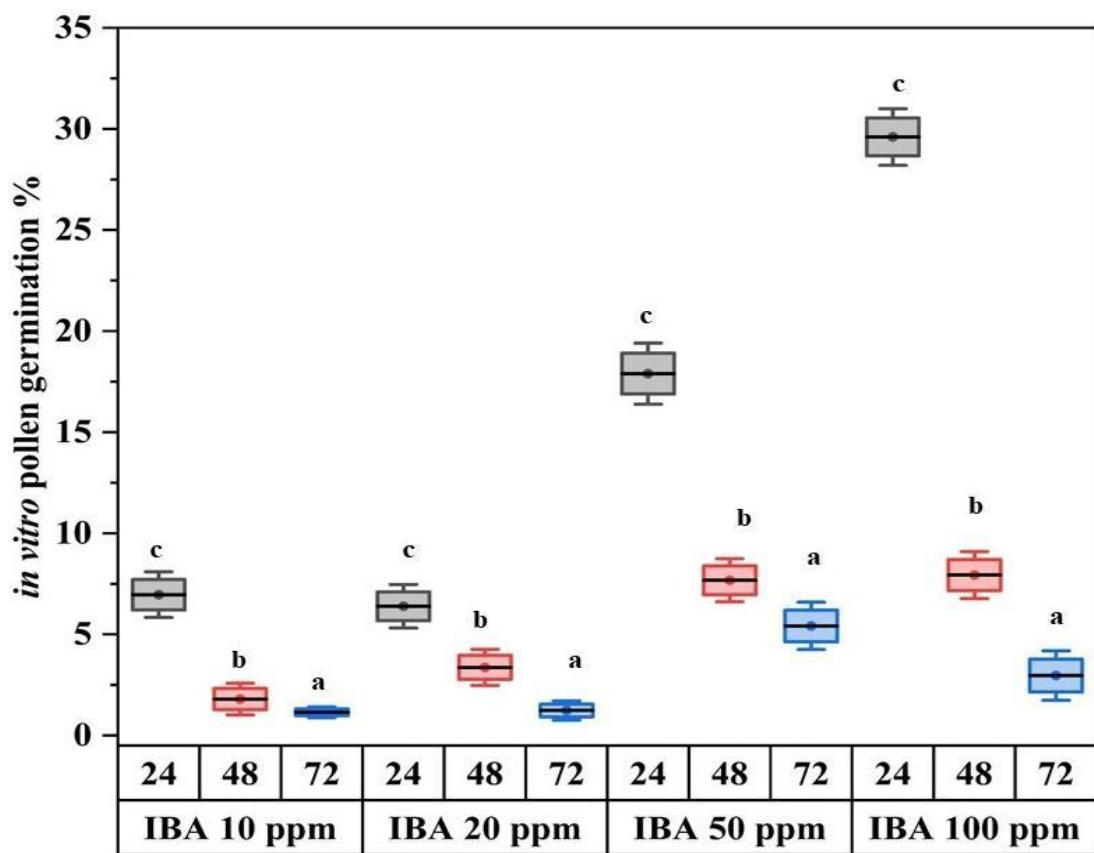


Figure 5.84. Effect of diff. conc. of IBA on *in vitro* pollen germination w.r.t. time.

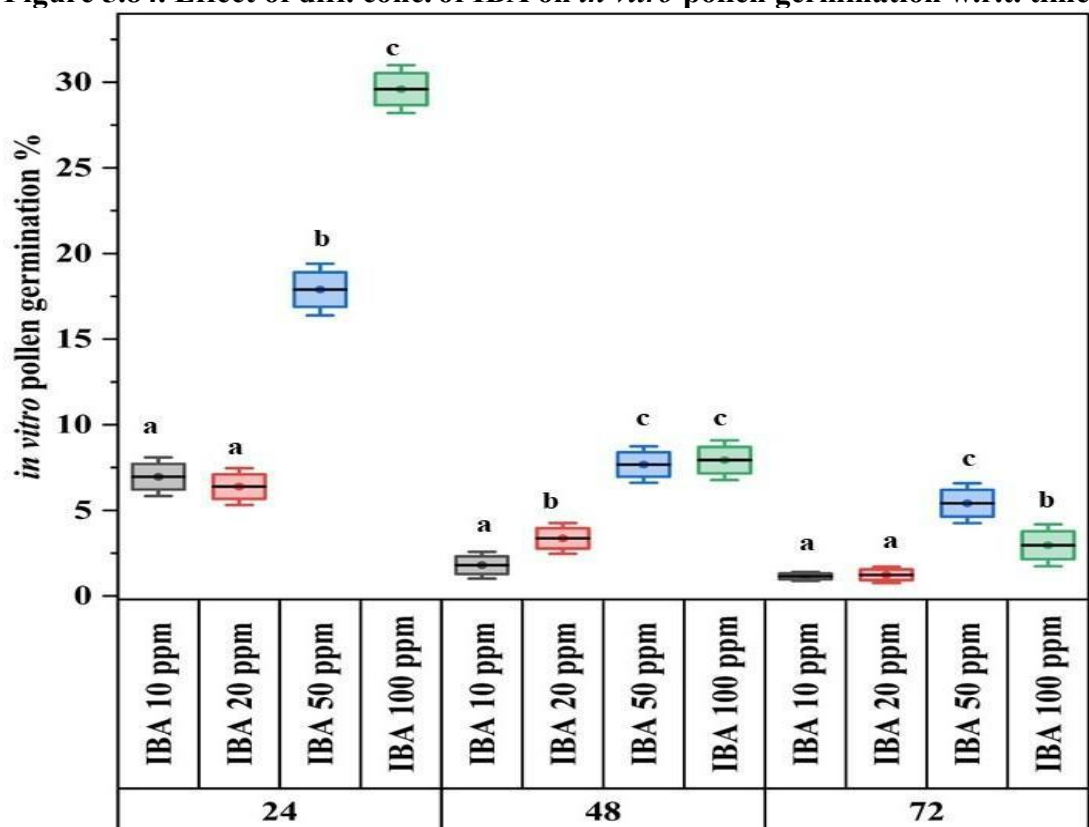


Figure 5.85. Effect of time on *in vitro* pollen germination w.r.t. diff. conc. of IBA.

0.77% for IBA 100 ppm. While significant differences were found between IBA 10 ppm and IBA 20 ppm with IBA 50 ppm and IBA 100 ppm, no significant difference was noted between IBA 50 ppm and IBA 100 ppm (Figure 5.85.). At the 72-hour mark, germination dropped to $1.15 \pm 0.17\%$ for IBA 10 ppm, $1.23 \pm 0.32\%$ for IBA 20 ppm, $5.42 \pm 0.78\%$ for IBA 50 ppm, and $2.96 \pm 0.82\%$ for IBA 100 ppm (Figure 5.85.). Again, a significant difference was observed between IBA 10 ppm and IBA 20 ppm with IBA 50 ppm and IBA 100 ppm, but no significant difference was found between IBA 10 ppm and IBA 20 ppm, or between IBA 50 ppm and IBA 100 ppm. These findings highlight that higher concentrations of IBA (50 ppm and 100 ppm) promote better pollen germination, particularly at the 24-hour interval, with a noticeable decline in germination over time. The results emphasize that IBA concentration significantly affects germination, the efficacy of IBA decreases with prolonged exposure, thereby providing insights into optimizing *in vitro* pollen germination for agricultural and research purposes.

5.11.8. Effect of different conc. of Kinetin on *in vitro* pollen germination w.r.t. time.

The effect of different concentrations of kinetin (K) on *in vitro* pollen germination was assessed over different concentrations of kinetin (K): K 10 ppm, K 20 ppm, K 50 ppm and K 100 ppm. For K 10 ppm, the initial germination percentage was $3.07 \pm 0.68\%$, which significantly decreased over time, dropping to $1.56 \pm 0.28\%$ at 48 hrs and $0.85 \pm 0.24\%$ at 72 hrs (Figure 5.86.). Similarly, K 20 ppm showed a decline from $7.62 \pm 0.58\%$ at 24 hrs to $4.65 \pm 0.48\%$ at 48 hrs and further reduced to $1.50 \pm 0.28\%$ at 72 hrs (Figure 5.86.). For K 50 ppm, the germination rate decreased from $9.16 \pm 0.78\%$ at 24 hrs to $4.91 \pm 0.59\%$ at 48 hrs, and $1.85 \pm 0.39\%$ at 72 hrs (Figure 5.86.). K 100 ppm, on the other hand, exhibited a marked reduction, starting from $3.22 \pm 0.35\%$ at 24 hrs to $0.95 \pm 0.22\%$ at 48 hrs and further declining to $0.72 \pm 0.17\%$ at 72 hrs (Figure 5.86.). Statistical analysis revealed significant differences in germination percentages across 24 hrs, 48 hrs, and 72 hrs for all treatments at the 0.01 level. The highest germination rates were observed at 24 hrs for all kinetin concentrations, with a clear decline as time progressed. These findings underscore the concentration-dependent

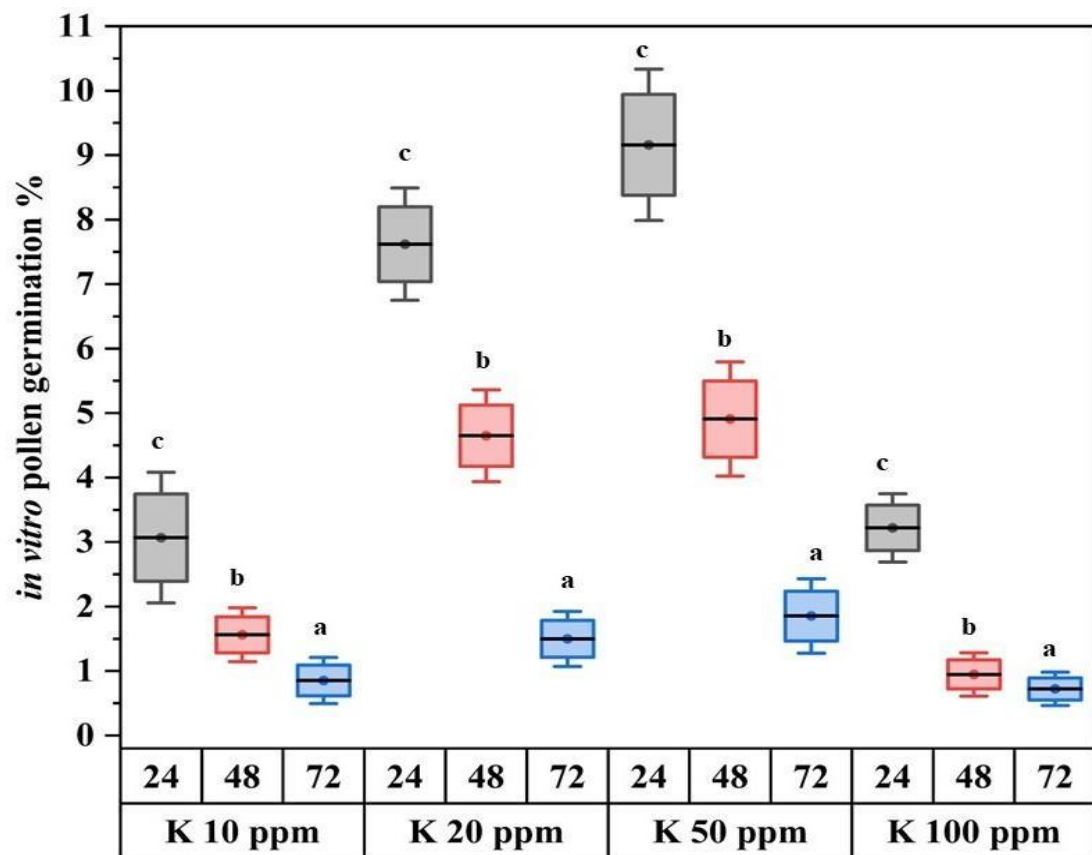


Figure 5.86. Effect of diff. conc. of K on *in vitro* pollen germination w.r.t. time.

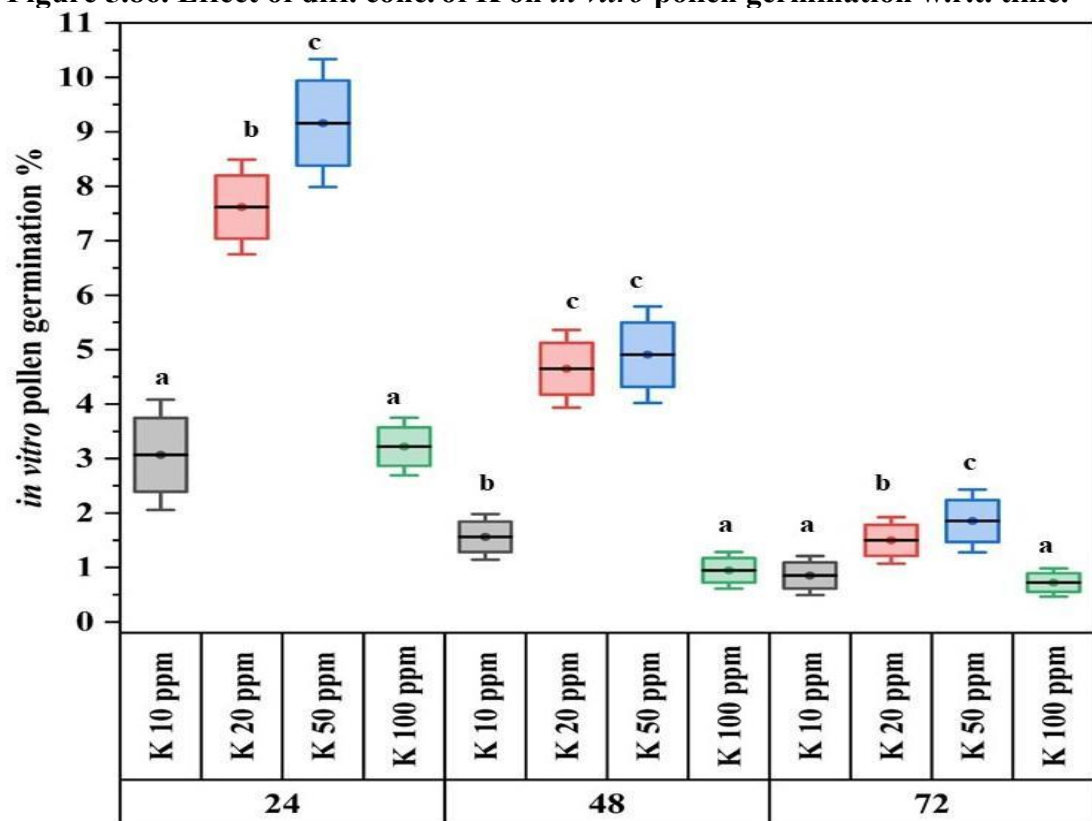


Figure 5.87. Effect of time on *in vitro* pollen germination w.r.t. diff. conc. of K.

effects of kinetin on pollen germination, highlighting that the most effective germination occurs within the first 24 hours of exposure.

5.11.9. Effect of time on *in vitro* pollen germination w.r.t. different concentration of Kinetin

The influence of time on *in vitro* pollen germination w.r.t. different concentrations of kinetin (K) was investigated across three time intervals: 24 hrs, 48 hrs, and 72 hrs. At 24 hrs, the highest germination rate was achieved with K 50 ppm ($9.16 \pm 0.78\%$), followed by K 20 ppm ($7.62 \pm 0.58\%$). In contrast, K 10 ppm ($3.07 \pm 0.68\%$) and K 100 ppm ($3.22 \pm 0.35\%$) exhibited much lower germination rates (Figure 5.87.). Statistical analysis indicated a significant difference at the 0.01 level between K 10 ppm and K 100 ppm with K 20 ppm and K 50 ppm, but no significant difference between K 10 ppm and K 100 ppm. At 48 hrs, the germination rates decreased across all treatments. K 10 ppm resulted in $1.56 \pm 0.28\%$, K 20 ppm in $4.65 \pm 0.48\%$, K 50 ppm in $4.91 \pm 0.59\%$, and K 100 ppm in $0.95 \pm 0.22\%$ (Figure 5.87.). A significant difference was found between K 20 ppm and K 50 ppm with K 10 ppm and K 100 ppm, but no significant difference was observed between K 20 ppm and K 50 ppm, indicating that higher concentrations of kinetin (20 ppm and 50 ppm) led to better pollen germination at this time point. At 72 hrs, the germination rates further declined to $0.85 \pm 0.24\%$ for K 10 ppm, $1.50 \pm 0.28\%$ for K 20 ppm, $1.85 \pm 0.39\%$ for K 50 ppm, and $0.72 \pm 0.17\%$ for K 100 ppm (Figure 5.87.). Similar to the previous time points, there was a significant difference between K 10 ppm and K 100 ppm with K 20 ppm and K 50 ppm, but no significant difference was observed between K 10 ppm and K 100 ppm. These results underscore the influence of kinetin concentration on pollen germination, with higher concentrations showing greater effectiveness, particularly during the initial 24 hrs. However, the effect of kinetin on germination diminished over time, suggesting that kinetin primarily affects germination during the early stages.

5.11.10. Effect of different conc. of GA₃ on *in vitro* pollen germination w.r.t. time.

The effect of different concentrations of gibberellic acid (GA₃) on *in vitro* pollen germination was assessed over varying concentrations of GA₃: GA₃ 10 ppm, GA₃ 20 ppm, GA₃ 50 ppm, and GA₃ 100 ppm. For GA₃ 10 ppm, the initial germination percentage was $5.62 \pm 0.59\%$, which significantly decreased over time, dropping to $1.61 \pm 0.30\%$ at 48 hrs and $0.76 \pm 0.19\%$ at 72 hrs (Figure 5.88.). Similarly, GA₃ 20 ppm showed a decline from $5.84 \pm 0.86\%$ at 24 hrs to $1.07 \pm 0.35\%$ at 48 hrs and further reduced to $1.14 \pm 0.22\%$ at 72 hrs. Statistically, in case of GA₃ 20 ppm, there is a significant difference between 24 hrs and both 48 hrs and 72 hrs but there is no significant difference between 48 hrs and 72 hrs (Figure 5.88.). For GA₃ 50 ppm, the germination rate decreased from $12.55 \pm 0.86\%$ at 24 hrs to $4.04 \pm 0.42\%$ at 48 hrs, and $2.88 \pm 0.42\%$ at 72 hrs (Figure 5.88.). GA₃ 100 ppm, on the other hand, exhibited a marked reduction, starting from $27.53 \pm 0.85\%$ at 24 hrs to $4.74 \pm 0.58\%$ at 48 hrs and further declining to $3.70 \pm 0.89\%$ at 72 hrs (Figure 5.88.). Statistical analysis revealed significant differences in germination percentages across 24 hrs, 48 hrs, and 72 hrs for GA₃ 10 ppm, GA₃ 20 ppm, GA₃ 50 ppm and GA₃ 100 ppm at the 0.01 level. These results indicate that while GA₃ enhances pollen germination, particularly at higher concentrations, the effect is time-dependent, with the most significant impact observed in the initial stages of germination. These findings underline the importance of optimizing both the concentration of GA₃ and the exposure duration to maximize pollen germination in *in vitro* conditions.

5.11.11. Effect of time on *in vitro* pollen germination w.r.t. diff. conc. of GA₃.

The effect of varying concentrations of gibberellic acid (GA₃) on *in vitro* pollen germination was evaluated across three time points: 24 hrs, 48 hrs, and 72 hrs. At 24 hrs, specifically, GA₃ 10 ppm resulted in a germination rate of $5.62 \pm 0.59\%$, GA₃ 20 ppm showed $5.84 \pm 0.86\%$, GA₃ 50 ppm exhibited $12.55 \pm 0.86\%$, and GA₃ 100 ppm had $27.53 \pm 0.85\%$ (Figure 5.89.). Statistical analysis revealed significant differences between GA₃ 10 ppm and GA₃ 100 ppm, as well as between GA₃ 20 ppm and GA₃ 50 ppm, but no significant difference was observed between GA₃ 10 ppm and GA₃ 20 ppm. At 48 hrs, a decrease in germination was evident across all concentrations, with

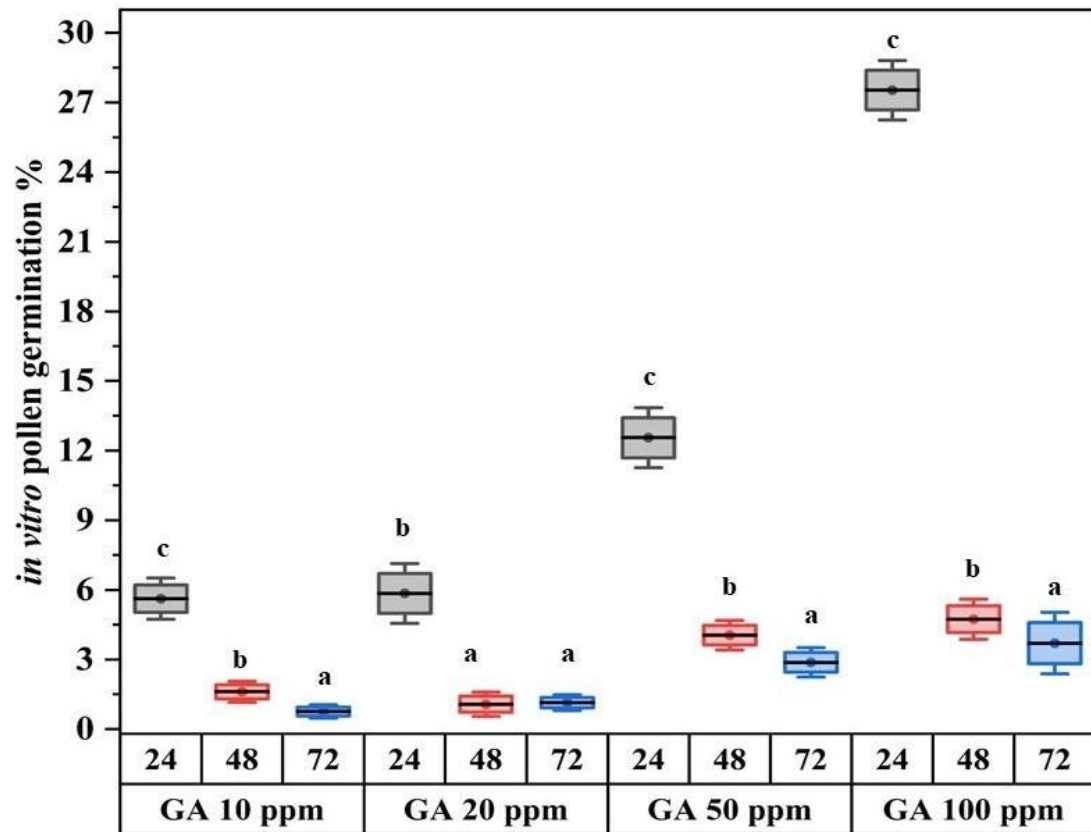


Figure 5.88. Effect of diff. conc. of GA₃ on *in vitro* pollen germination w.r.t. time.

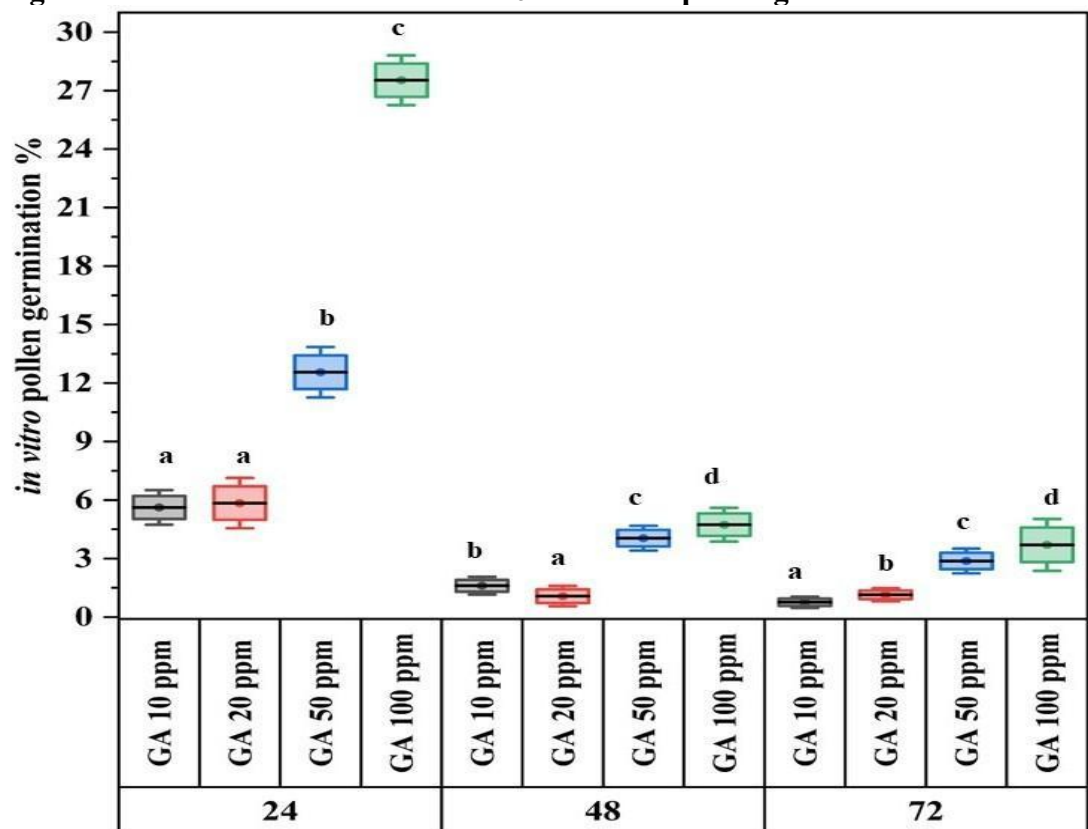


Figure 5.89. Effect of time on *in vitro* pollen germination w.r.t. diff. conc. of GA₃.

GA₃ 10 ppm at $1.61 \pm 0.30\%$, GA₃ 20 ppm at $1.07 \pm 0.35\%$, GA₃ 50 ppm at $4.04 \pm 0.42\%$, and GA₃ 100 ppm at $4.74 \pm 0.58\%$ (Figure 5.89.). The statistical analysis indicated significant differences between all treatments, suggesting that higher concentrations of GA₃ were more effective in promoting pollen germination. At the 72-hour mark, the germination rates continued to decline, with GA₃ 10 ppm at $0.76 \pm 0.19\%$, GA₃ 20 ppm at $1.14 \pm 0.22\%$, GA₃ 50 ppm at $2.88 \pm 0.42\%$, and GA₃ 100 ppm at $3.70 \pm 0.89\%$ (Figure 5.89.). Similar to the previous time points, significant differences were observed between all concentrations at the 0.01 level. These findings underscore the concentration-dependent effects of GA₃ on pollen germination, with higher concentrations resulting in better germination rates, particularly at 24 hrs. However, the effectiveness of GA₃ decreased over time, indicating that its impact on pollen germination is most prominent in the first 24 hours.

5.11.12. Effect of different conc. of plant growth regulators on *in vitro* pollen germination.

The effect of various plant growth regulators (IAA, IBA, K, and GA₃) at different concentrations on *in vitro* pollen germination was investigated. Among the IAA treatments, 50 ppm induced the highest germination rate (7.69 %), followed by 100 ppm (6.89%), 20 ppm (3.98%), and 10 ppm (2.58 %) (Figure 5.90.). These results indicate a concentration-dependent response, with higher IAA concentrations promoting increased germination, although there was considerable variation in the results, particularly at the 50 ppm concentration. For IBA, the germination rate peaked at 100 ppm (13.50%), followed by 50 ppm (10.33%), 20 ppm (3.66%), and 10 ppm (3.30%) (Figure 5.90.). These findings suggest that IBA effectively promotes pollen germination at higher concentrations, though the data exhibited significant variability, especially at 100 ppm. For kinetin (K), the highest germination was observed at 50 ppm (5.31%), followed by 20 ppm (4.59%), 10 ppm (1.83%), and 100 ppm (1.63%) (Figure 5.90.). These results show that kinetin enhances pollen germination, particularly at 50 ppm, but with a lower overall effectiveness compared to IBA and GA₃. Regarding GA₃, the highest germination was observed at 100 ppm (11.99%), followed by 50 ppm (6.49%), 20 ppm (2.69%), and 10 ppm (2.66%) (Figure 5.90.).

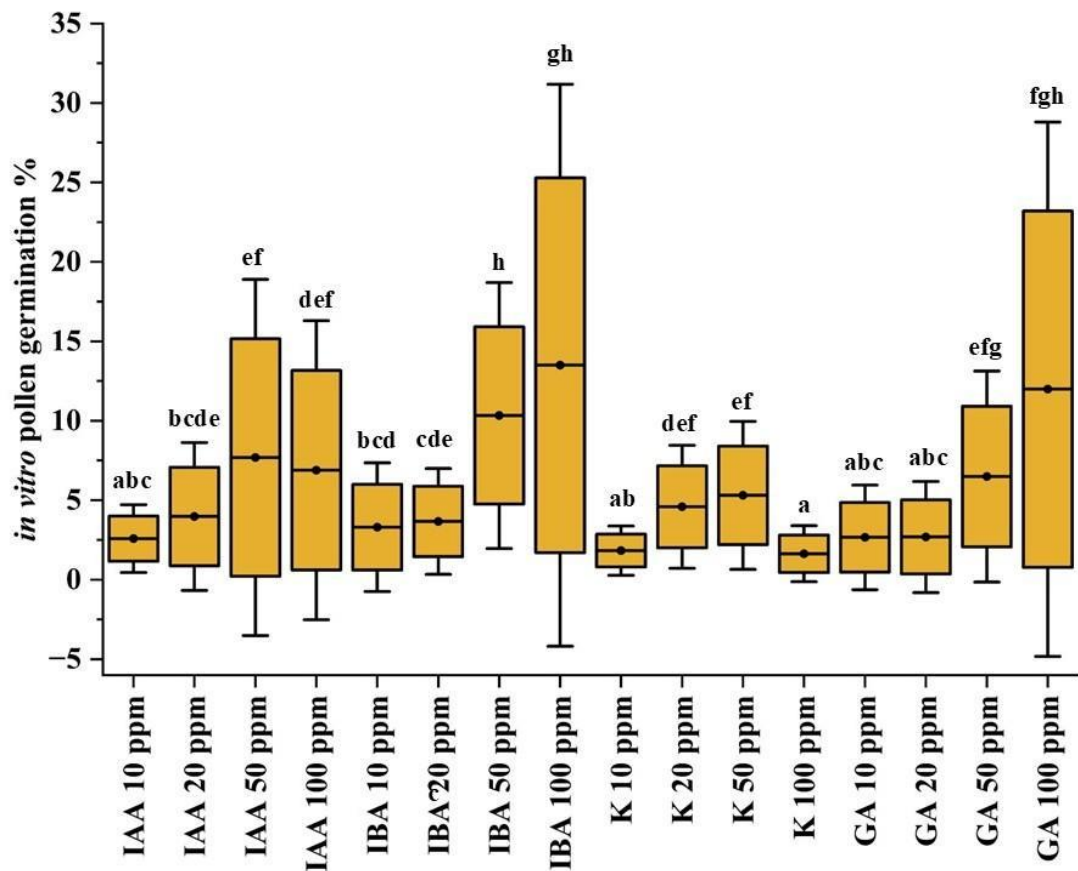


Figure 5.90. Effect of diff. conc. of plant growth regulators on *in vitro* pollen germination.

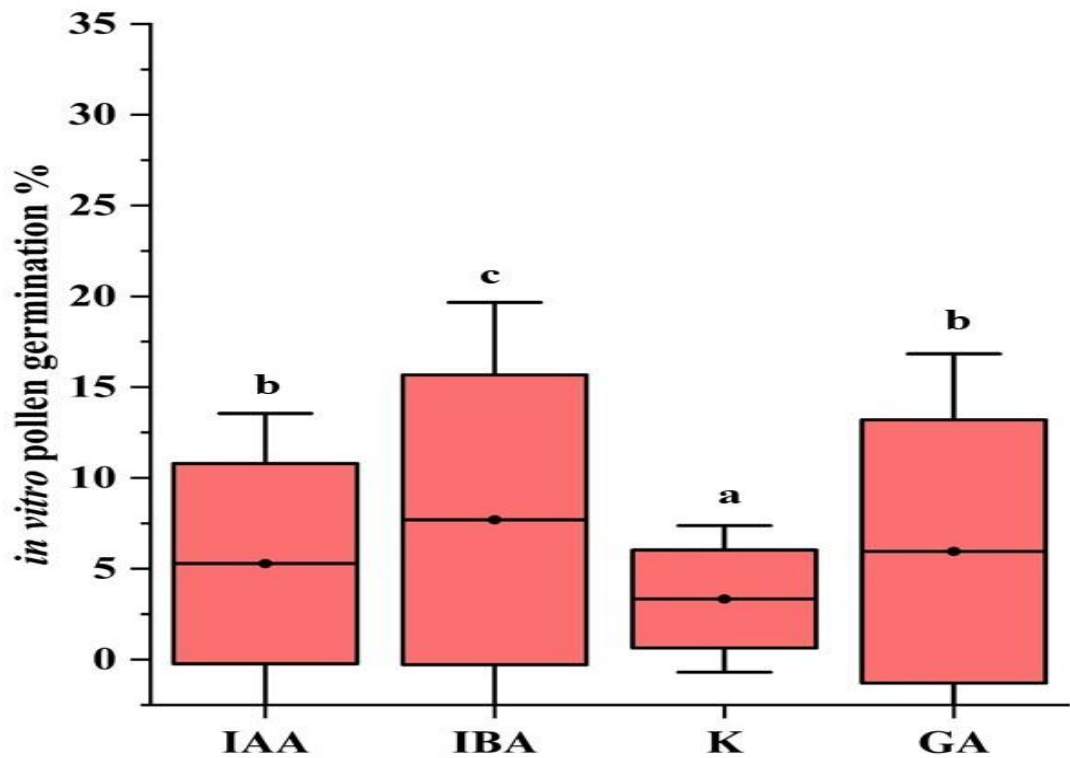


Figure 5.91. Effect of diff. plant growth regulators on *in vitro* pollen germination.

These findings suggest that GA₃ at higher concentrations, particularly 100 ppm, significantly enhances germination, although there was considerable variability. In summary, the data indicate that IBA and GA₃, particularly at 100 ppm, are the most effective growth regulators for promoting pollen germination, although the results also highlight substantial variability in germination across different concentrations. The results underscore the importance of optimizing both the concentration and the type of plant growth regulator to maximize *in vitro* pollen germination, with implications for plant breeding and biotechnological applications.

5.11.13. Effect of different plant growth regulators on *in vitro* pollen germination.

The effects of various plant growth regulators (IAA, IBA, K, and GA₃) on *in vitro* pollen germination were investigated, and the results are presented in the table. The germination percentages ranged from 3.34% to 7.70%, with IBA (Indole-3-butyric acid) eliciting the highest germination percentage at 7.70%, followed by GA₃ (Gibberellic acid) with 5.96%, IAA (Indole-3-acetic acid) at 5.28%, and K (Kinetin) showing the lowest germination percentage at 3.34% (Figure 5.91.). The standard deviations for the treatments varied, with IBA exhibiting the highest variability (7.98), indicating a significant spread in the response of pollen to this regulator. K showed the least variability with a standard deviation of 2.69. A detailed statistical analysis confirmed a significant difference between the effects of the different plant growth regulators on *in vitro* pollen germination, with a p-value less than 0.01, indicating that the observed differences are statistically significant. These findings highlight the differential impact of PGRs on *in vitro* pollen germination, underscoring the necessity of selecting appropriate growth regulators for optimizing *in vitro* pollen germination in controlled environments. The results provide important insights into the role of these regulators in enhancing or inhibiting germination, which is critical for improving fertilization efficiency and subsequent crop productivity.

5.11.14. Spearman's rank correlation analysis between concentration, time, sucrose, and hormones.

Spearman's rank correlation analysis was employed to explore the relationships between concentration, time, sucrose, and various hormones, including IAA, IBA, K, and GA₃, as summarized in Table 5.22.. The analysis revealed that concentration exhibited significant positive correlations with IAA ($r_s = 0.252^{**}$, $p < 0.01$), IBA ($r_s = 0.559^{**}$, $p < 0.01$), GA₃ ($r_s = 0.477^{**}$, $p < 0.01$), and sucrose ($r_s = 0.341^{**}$, $p < 0.01$), indicating that higher concentrations are associated with elevated levels of these variables. The strongest correlations were observed with IBA and GA₃, suggesting a more pronounced interaction between concentration and these hormones compared to IAA and sucrose. In contrast, time demonstrated significant negative correlations with all variables, including IAA ($r_s = -0.923^{**}$, $p < 0.01$), IBA ($r_s = -0.723^{**}$, $p < 0.01$), K ($r_s = -0.712^{**}$, $p < 0.01$), GA₃ ($r_s = -0.771^{**}$, $p < 0.01$), and sucrose ($r_s = -0.456^{**}$, $p < 0.01$) (Table 5.22.). Moreover, significant positive correlations were found among the hormones themselves, particularly between IAA and IBA ($r_s = 0.826^{**}$, $p < 0.01$), IAA and GA₃ ($r_s = 0.834^{**}$, $p < 0.01$), and IBA and GA₃ ($r_s = 0.866^{**}$, $p < 0.01$), which suggests a strong interdependence between these plant hormones. Additionally, Kinetin (K) showed moderate positive correlations with both GA₃ ($r_s = 0.454^{**}$, $p < 0.01$) and sucrose ($r_s = 0.557^{**}$, $p < 0.01$) (Table 5.22.). These findings highlight the complex and interconnected nature of the relationships between concentration, time, sucrose, and hormonal activity, and suggest that further investigation into the underlying mechanisms driving these correlations could provide valuable insights into *in vitro* pollen germination and development processes.

5.11.15. Effect of temperature on *in vitro* pollen germination.

The impact of temp. on *in vitro* pollen germination was examined at four different temp. levels: 15°C, 20°C, 25°C, and 30°C. The results revealed that pollen germination was most favorable at 25°C, with a mean germination rate of 89.13 ± 2.91 % (Figure 5.92.). This indicates that 25°C is the optimal temperature for promoting pollen germination *in vitro*. At 20°C, germination was slightly lower (78.08 ± 3.72 %), but still significant, suggesting that moderate temperatures also support germination,

Table 5.22. Spearman's rank correlation analysis between concentration, time, sucrose, and hormones.

	IAA		IBA		K		GA		Sucrose	
	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p
Concentration	0.252**	0.005	0.559**	0.000	-0.063	0.491	0.477**	0.000	0.341**	0.000
Time	-0.923**	0.000	-0.723**	0.000	-0.712**	0.000	-0.771**	0.000	-0.456**	0.000
IAA	1	-	0.826**	0.000	0.696**	0.000	0.834**	0.000	0.620**	0.000
IBA	0.826**	0.000	1	-	0.527**	0.000	0.866**	0.000	0.564**	0.000
K	0.696**	0.000	0.527**	0.000	1	-	0.454**	0.000	0.557**	0.000
GA	0.834**	0.000	0.866**	0.000	0.454**	0.000	1	-	0.433**	0.000
Sucrose	0.620**	0.000	0.564**	0.000	0.557**	0.000	0.433**	0.000	1	-

** Correlation is significant at the 0.01 level.

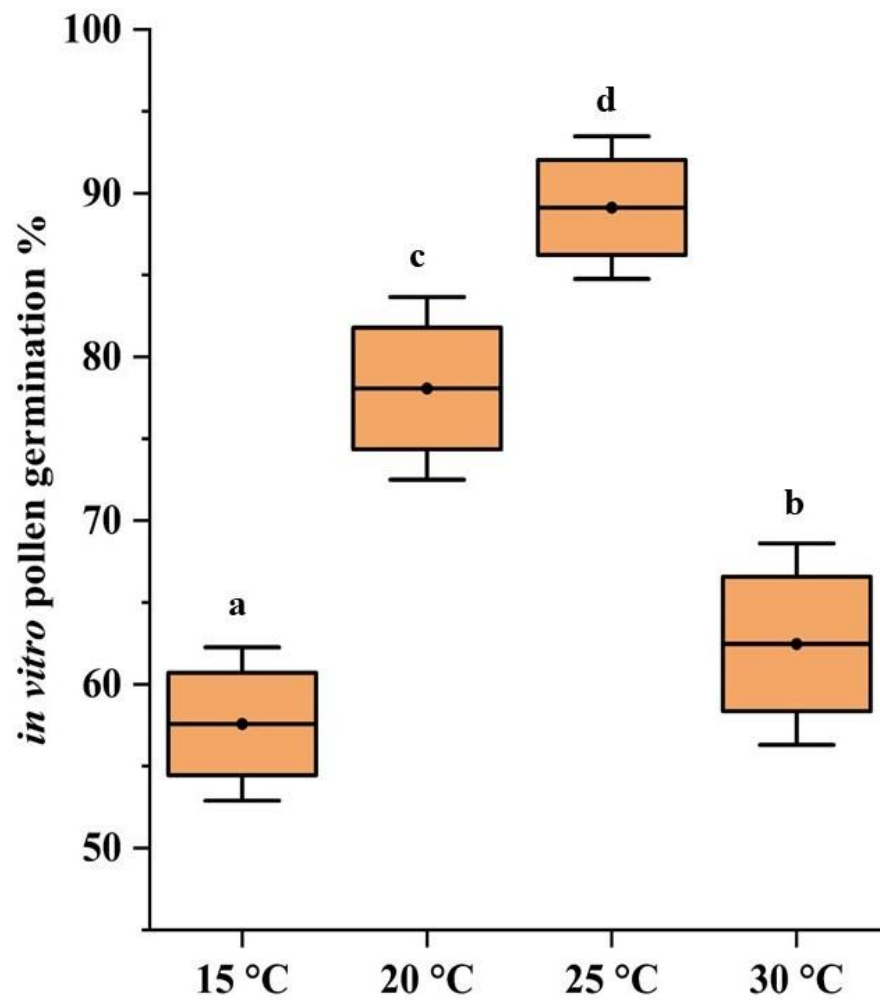


Figure 5.92. Effect of temperature on *in vitro* pollen germination.

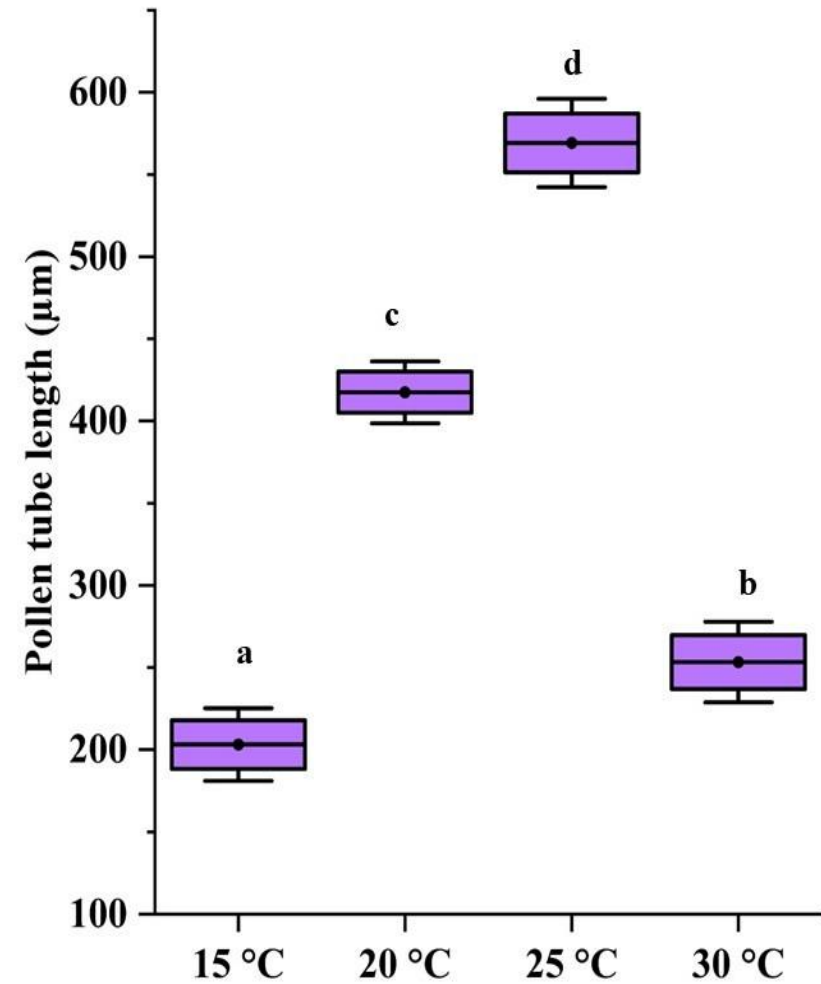


Figure 5.93. Effect of temperature on pollen tube length.

though less effectively than 25°C (Figure 5.92.). In contrast, at 15°C, pollen germination decreased notably (57.57 ± 3.13 %), indicating that lower temperatures inhibit germination. The lowest germination was observed at 30°C, with a mean of 62.46 ± 4.11 %, highlighting that high temperatures have a detrimental effect on pollen germination, despite being higher than at 15°C (Figure 5.92.). The standard deviations observed at 20°C and 30°C indicate variability in germination responses, particularly at the higher temperature. These findings emphasize the critical role temperature plays in regulating pollen germination, with 25°C being the most favorable temperature. The results also suggest that both lower and higher temperatures negatively affect the germination process, which has important implications for optimizing *in vitro* culture conditions in plant breeding and biotechnology.

5.11.16. Effect of temperature on pollen tube length.

The influence of temperature on pollen tube length was investigated at four different temperature points: 15°C, 20°C, 25°C, and 30°C. At 15°C, the average pollen tube length measured 203.19 ± 14.72 µm, indicating relatively low growth (Figure 5.93.). As the temperature increased to 20°C, a significant rise in pollen tube length was observed, reaching 417.53 µm, accompanied by a decrease in SD to 12.55, suggesting reduced variation at this temperature (Figure 5.93.). A further increase in temperature to 25°C resulted in the highest observed pollen tube length of 569.21 µm, though with a higher SD of 17.93, indicating more variability in tube lengths at this optimal temperature. However, at 30°C, a notable decrease in pollen tube length was recorded, dropping to 253.37 ± 16.38 µm (Figure 5.93.). These findings suggest a temperature dependent response of pollen tube elongation, with maximum growth occurring at 25°C. Both lower (15°C) and higher (30°C) temperatures were associated with suboptimal pollen tube length, highlighting the narrow temperature window for optimal pollen tube elongation. This study underscores the importance of temperature as a critical factor in pollen tube growth and provides insight into the thermal constraints affecting reproductive success in plants.

5.11.17. Spearman's rank correlation analysis between temperature, pollen germination and pollen tube length.

Spearman's rank correlation analysis was conducted to investigate the relationships between temperature, pollen germination, and pollen tube length, with the results summarized in Table 5.23. A moderate positive correlation was observed between temperature and pollen germination ($r_s = 0.387^*$, $p < 0.05$), as well as between temperature and pollen tube length ($r_s = 0.387^*$, $p < 0.05$). These correlations were statistically significant at the 0.05 level, suggesting that higher temperatures are associated with increases in both pollen germination and pollen tube elongation. Additionally, a very strong positive correlation was found between pollen germination and pollen tube length ($r_s = 0.935^{**}$, $p < 0.01$), which was highly significant at the 0.01 level (Table 5.23.). This indicates that as the percentage of pollen germination increases, so does the length of the pollen tube. These results provide compelling evidence of the critical role that temperature plays in enhancing pollen germination and tube development, with the germination process serving as a key determinant of tube elongation. The findings have important implications for understanding the environmental factors influencing plant reproduction, particularly in the context of climate change, where temperature fluctuations could potentially affect pollen function and reproductive success.

Table 5.23. Spearman's rank correlation analysis between temperature, pollen germination and pollen tube length.

	Pollen germination (%)		Pollen tube length	
	r_s	p	r_s	p
Temperature	0.387*	0.014	0.387*	0.014
Pollen germination	1	-	0.935**	0.000
Pollen tube length	0.935**	0.000	1	-

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

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

CHAPTER 6

DISCUSSION

6.1. Reproductive phenology of *P. timoriana*: spatio-temporal variation across different elevations

The reproductive phenology of *P. timoriana* across the three distinct sites - Sairang, Tanhril, and Reiek, exhibits notable spatio-temporal variation in response to local environmental conditions. This study provides significant insights into how elevation and climatic variables such as temperature, humidity, wind speed, and soil moisture influence the timing and success of flowering and fruiting stages in *P. timoriana*.

The onset of flowering, peak flowering, and fruit formation events across the three sites showed clear temporal shifts over the years. At the lowest elevation site (Sairang), flowering onset exhibited a consistent delay over the study period, with a shift from November 7th in 2021-2022 to November 12th in 2023-2024. This delay could be linked to increasing temperatures over time, which have been shown to inhibit the timing of flowering in other plant species (Tun *et al.*, 2021). Similar delays were observed at Tanhril, though to a lesser extent, and at Reiek, the highest elevation site, flowering onset remained relatively stable across the three years, suggesting that elevation may mitigate some of the impacts of temperature variations on flowering timing. This is consistent with the observations of Elmendorf *et al.* (2023), who noted that elevation moderates temperature fluctuations, potentially stabilizing phenological events.

Flowering duration exhibited both site-specific and temporal trends. At Sairang, flowering duration gradually increased from 50 days in 2021-2022 to 54 days in 2023-2024, possibly due to the extended warm periods, which can lead to prolonged flowering in tropical species (Ha, 2014). In contrast, the flowering duration at Tanhril and Reiek decreased, particularly at Tanhril, where a reduction in flowering duration was noted over the years. This suggests that higher elevations with cooler

temperatures, as seen in Reiek, might restrict flowering periods, potentially due to a shorter growing season (Inouye & Wielgolaski, 2025; Haggerty & Galloway, 2011).

The peak flowering dates showed significant variation, with shifts occurring in the earlier years at lower elevations and in later years at higher elevations, a phenomenon consistent with the concept of phenological lag at higher elevations (Arroyo *et al.*, 2021; Vitasse *et al.*, 2018; Mulder *et al.*, 2017). These findings highlight the sensitivity of *P. timoriana* to environmental conditions, particularly temperature, which influences both flowering duration and the timing of peak flowering. The relationship between temperature and flowering time has been well-documented in other species, with warmer temperatures generally advancing flowering in some species but delaying it in others, depending on their phenological sensitivity (Mulder *et al.*, 2017; Wang *et al.*, 2014; Springate & Kover, 2014; Iler *et al.*, 2013).

Amplitude, a measure of flowering intensity, increased over time, especially at Sairang. The observed increase in amplitude at the population level, particularly at Sairang, suggests that despite delayed flowering onset, the overall intensity of flowering may have intensified, possibly due to more favorable environmental conditions in later years (Austin *et al.*, 2024; Dorji *et al.*, 2020). In contrast, the amplitude at Reiek showed a slight decrease over the years, which could reflect the harsher conditions associated with higher elevation that may limit the overall reproductive capacity of plants.

Flowering synchrony, which measures the coordination of flowering events within the population, showed mixed trends. The increase in synchrony at Sairang and Reiek suggests that these sites may experience more consistent weather patterns conducive to synchronized flowering. In contrast, the slight decline in synchrony at Tanhril, which is located at an intermediate elevation, could indicate more variable climatic conditions or micro-environmental factors that disrupt flowering coordination (Chen *et al.*, 2024).

The analysis of environmental correlations revealed complex interactions between climatic variables and reproductive phenology. Temperature, both maximum and minimum, played a significant role in delaying flowering and fruit formation across

all sites. This aligns with findings from other studies that highlight the negative impact of rising temperatures on plant reproductive timing (Qian *et al.*, 2025; Alquichire-Rojas *et al.*, 2024). However, the positive correlation between warmer temperatures and fruit maturation underlines the potential for climate induced shifts in plant reproductive success, which might be observed under specific environmental conditions that favor fruit maturation.

Humidity showed contrasting effects on different reproductive stages. While higher humidity positively correlated with flowering, it negatively impacted fruit formation and maturation, particularly at lower elevations. This inverse relationship could be attributed to the fact that excessive moisture during fruit development may promote fungal infections or cause other physiological stress, as noted in similar studies (Hossain *et al.*, 2024). The findings suggest that while humid conditions may initiate flowering, they may impair later reproductive stages.

Precipitation also negatively affected flowering and fruit formation, which is consistent with previous reports suggesting that excessive rainfall during the reproductive phase can impede pollination and fruit set in tropical plants (Frigero *et al.*, 2025; Raju *et al.*, 2024). Wind speed, interestingly, showed positive correlations with finished flowering and fruit formation, which may be due to the mechanical dispersal of pollen or the enhancement of pollinator activity in windy conditions (Crall *et al.*, 2020; Young *et al.*, 2018).

The regression models applied in this study further underscore the importance of environmental variables in predicting the success of reproductive phenology. Root zone soil wetness (RZSW) and relative humidity (RH) emerged as significant predictors for fruit maturation, suggesting that these factors directly influence the final stages of reproductive development. Similarly, fruit formation was significantly influenced by temperature, with maximum temperature (TM) and maximum wind speed (WSMA) showing strong predictive relationships. These findings corroborate the work of Raju *et al.* (2024), who found that soil moisture and temperature are key determinants of fruiting success in tropical species. The predictive models developed

in this study could be used to forecast future reproductive trends under varying climatic scenarios, offering valuable insights for conservation efforts and agricultural practices.

6.2. Floral biology of *P. timoriana*: temporal dynamics of anthesis, anther dehiscence, and stigma receptivity

The floral biology of *P. timoriana* demonstrates a complex interplay of morphological traits and ecological interactions, which are critical for the successful transfer of pollen and subsequent fertilization. The anthesis of *P. timoriana*, observed to peak between 17:00 and 19:00, aligned strategically with the activity patterns of key pollinators (Singh *et al.* 2024). Similar pattern of anthesis was reported in *P. platycephala* (Chaves *et al.*, 2020). This pattern aligns with similar studies conducted on other tropical species, where the late afternoon and early evening are identified as periods of maximal blooming activity (Gomasta *et al.*, 2025; Gomes *et al.*, 2024; Saini & Sihag, 2020). This temporal synchronization is critical, as it ensured that flowers are most accessible with pollen loads when pollinator activity is at its height (Balducci *et al.* 2020; Ferreira *et al.* 2018; van Tussenbroek *et al.* 2008). The rapid and synchronous opening of flowers not only enhances the concentration of pollen available for visiting pollinators but also promotes cross-pollination among the flowers. Such genetic mixing is vital for maintaining genetic diversity, which in turn contributes to population resilience in changing environmental conditions (Fornoff *et al.*, 2017; Sun *et al.*, 2010; Tachiki *et al.*, 2010). Moreover, the extended availability of flowers with receptive stigma, remained open for one to two days and accommodating both diurnal and nocturnal pollinators, illustrates a significant adaptation to attract a broad array of pollinator species (Singh *et al.*, 2024). This strategy not only increases the likelihood of successful fertilization but also diversifies the plant's pollination network, which is particularly important in environments with fluctuating pollinator populations and climate.

The dynamics of anther dehiscence in *P. timoriana* are closely tied to the timing of anthesis. Notably, the peak anthesis period between 17:00 and 19:00 hours, during which approximately 60% of flowers attain full bloom, coincides with the activity of both diurnal and nocturnal pollinators. Flowers that open during this window,

remained open throughout the night and into the subsequent days, thereby increasing the temporal overlap with pollinator activity and enhancing the likelihood of successful pollination (Kendall & Nicholson, 2025; Singh *et al.*, 2024; Teng *et al.*, 2024). The observed synchronization, where dehiscence begins shortly after flower opening and peaks in alignment with stigmatic receptivity, underscores the evolutionary importance of these processes (Thorat *et al.*, 2020; Crispim *et al.*, 2017; Aleemullah *et al.*, 2000). This synchronized blooming is a prevalent phenomenon among tropical species, aligning anthesis with peak pollinator activity to optimize cross-pollination opportunities (Sabu, 2024; Deyto & Cervancia, 2022; Veereshkumar *et al.*, 2021). The longitudinal dehiscence pattern, characterized by the splitting of anther lobes, facilitates the abundant efficient release of pollen. This adaptation ensures that pollen is readily available for pollinators immediately following the critical period of anthesis, optimizing the chances of successful fertilization (Li *et al.*, 2014; Wilson *et al.*, 2011; Matsui *et al.*, 1999). The nearly complete dehiscence of anthers by midnight indicates a strategic reproductive timing that maximizes pollen availability during peak pollinator activity. Continuous pollen release over a four-hour period aligns with the natural behavior of pollinators, ensuring that pollen is accessible when pollinators visit the flowers (Khanduri & Kumar, 2017a; Reddi *et al.*, 1988; Goodwin, 1986). Such finely tuned synchronization between flowering and pollen release is indicative of the evolutionary pressures faced by *P. timoriana* in its quest for reproductive success. In comparison to related species, anther dehiscence in *P. platycephala* also exhibits strong synchronization with pollinator activity, although the timing may vary based on local climatic conditions and pollinator behaviors (Chaves *et al.*, 2020).

Assessments of stigma receptivity using peroxidase and esterase activity assays revealed that stigma receptivity in *P. timoriana* follows distinct temporal patterns closely correlated with anthesis and slight protandrous anther dehiscence. The peak peroxidase activity recorded between 21:00 and 23:00 suggests that stigmas are most receptive shortly after the majority of pollen is released, which is crucial for ensuring that pollen transferred during peak pollinator activity can effectively fertilize the ovules (Thorat *et al.*, 2020; Crispim *et al.*, 2017). In line with recent studies,

temperature is recognized as a key factor in floral processes, with elevated temperatures accelerating floral development and pollinator attraction (Alquichire-Rojas *et al.*, 2024; Creux *et al.*, 2021; Scaven & Rafferty, 2013). The negative correlation between temperature and stigma receptivity that was observed in the present study is consistent with the findings of Qian *et al.* (2025) and Fábíán *et al.* (2019). Temperature was strongly and positively correlated with anther dehiscence and anthesis, reflecting the direct impact of temperature on the timing and quality of reproductive events (Wani *et al.*, 2022; Matsui & Hasegawa, 2019; Khanduri, 2011). In contrast, relative humidity (RH) exhibited a positive correlation with stigma receptivity, indicating that higher moisture levels support stigma function, a finding consistent with studies that demonstrate the importance of humidity in pollen germination and stigma function (Jamshed *et al.*, 2020; Matsui & Hasegawa, 2019). However, RH negatively influenced both anther dehiscence and anthesis, suggesting that excessive moisture may hinder the dispersal of pollen and the opening of flowers (Kampová *et al.*, 2024; Pena & Wolfe, 2023). Wind speed (WS) had a positive relationship with stigma receptivity, but negatively impacted anthesis, highlighting the dual role of wind in pollination processes, where wind can aid in stigma exposure but hinder the release of pollen (Lu *et al.*, 2008; Qu *et al.*, 2007). These findings underscore the significance of studying plant-pollinator interactions within the framework of environmental variability, as these interactions are pivotal for understanding economic fruit yield, ecosystem dynamics and plant community structure. These results highlight the critical role of species-specific research in understanding both the responses of tree species and the underlying mechanisms driving their adaptation to shifts in climatic conditions, particularly within the tropical semi-evergreen forests of the Indo-Burma biodiversity hotspot.

6.3. Pollen morphology of *P. timoriana*

Polyads, clusters of pollen grains that remain united during dispersal, display remarkable morphological diversity across different plant families. This diversity reflects evolutionary adaptations to specific ecological and reproductive demands. Among angiosperms, Fabaceae provides a particularly rich example of this diversity. Polyads in Fabaceae vary significantly in grain number, arrangement, and overall

structure, correlating with the environmental conditions and pollination strategies of the species (Alrawi *et al.*, 2023; Soares *et al.*, 2022; Luz *et al.*, 2013).

In *Acacia* species, polyads typically consist of 16 grains arranged in a dense, spherical structure (Duarte *et al.*, 2021) similar to that of *P. timoriana*, though with fewer grains. This compact morphology is particularly advantageous in arid habitats, where *Acacia* species are commonly found (Alqarni *et al.*, 2017). The cohesive arrangement ensures the integrity of the polyads during transport by pollinators, reducing the likelihood of grain loss or desiccation in harsh conditions. This feature is a clear adaptation to the ecological challenges posed by these environments (Soares *et al.*, 2022). Conversely, *Mimosa* species exhibit polyads with 8–16 grains arranged in a flatter, disc-like structure. This morphology enables polyads to fit within the specialized floral structures characteristic of *Mimosa* flowers. Such precision facilitates efficient attachment to insect pollinators, optimizing pollen transfer within specialized pollination systems. The flatter polyad design exemplifies co-evolution between *Mimosa* species and their specific pollinators, demonstrating how morphological variations can enhance reproductive efficiency (Seijo & Neffa, 2004).

Stryphnodendron species produce asymmetrical polyads, where the uneven distribution of pollen grains may support differential dispersal strategies (Soares *et al.*, 2022). Polyads are present in all genera of the *Piptadenia* group, though significant variation in their characteristics is observed. These variations include: (1) shape, ranging from sub-sphaeroidal to more commonly ovoidal, and occasionally biconvex; (2) grain count, which can be 8, 12, 16, 20, or 32; and (3) an irregular arrangement of pollen grains. Such traits can vary within the same genus (*Piptadenia*, *Mimosa*, *Stryphnodendron*) and, less frequently, within the same species (e.g., *Piptadeniopsis lomentifera*, *Anadenanthera* spp.). In genera like *Adenopodia* and *Anadenanthera*, flattened polyads are predominant, although sub-sphaeroidal polyads are also common. Dissymmetric shapes are typical in species of *Stryphnodendron*, *Piptadenia*, and *Piptadeniopsis*. Bitetrads are observed in *Piptadeniopsis*, *Microlobius*, and certain species of *Mimosa* and *Piptadenia*, with tetrads and/or polyads also present within these taxa. The most irregular pollen arrangements are found in *Stryphnodendron*, *Piptadenia*, *Parapiptadenia*, and *Marlimorimia* (Caccavari, 2002). In contrast, *Albizia*

species feature symmetrical polyads of 16 grains, aligning with more generalist pollination strategies (Soares *et al.*, 2022; Wyatt & Lipow, 2021). These differences underline the ecological flexibility and evolutionary adaptability within Fabaceae. The morphological diversity of polyads underscores their critical role in angiosperm reproductive success. Variations in grain number, structure, and arrangement enable plants to adapt to diverse ecological niches and pollination mechanisms. Polyads also serve as important taxonomic markers, aiding in the identification and classification of species and genera. By linking morphology to function, the study of polyads reveals the evolutionary ingenuity of plants in meeting ecological challenges and ensuring reproductive success (Luz *et al.*, 2013; Harder & Johnson, 2008; Seijo & Neffa, 2004).

6.4. Pollinator behavior and visitation patterns

The temporal visitation patterns of pollinators in this study reveal significant variability across different species and years, providing important insights into how environmental and ecological factors influence their activity. Species such as *Camponotus* spp., *Tapinoma sessile*, *Bombus bicoloratus*, *Apis cerana indica*, and others exhibited temporal fluctuations in visitation frequency, with distinct peaks and troughs occurring during specific time blocks throughout the day and night. In 2021, *A. cerana indica* recorded the highest visitation frequency among the species, with an average of 17.63 visits per 2 hours. This was followed by bat and *T. sessile* with visitation frequencies of 11.63 and 8.29 visits per 2 hours, respectively. These findings corroborate those of Young *et al.* (2021) and Chapman *et al.* (2022), who demonstrated that bee species tend to exhibit higher foraging activity during daylight hours, with pronounced declines during the night. However, *Camponotus* spp. and *Vespa affinis* exhibited lower visitation frequencies, suggesting that these species may have more specialized or less frequent foraging behaviors (Rojas-Nossa & Calviño-Cancela, 2020; Gaffney, 2016; Yamamoto & Del-Claro, 2008).

Across both years, a general pattern of decreased visitation was observed in 2022 relative to 2021, with a notable reduction in activity during early morning and late-night periods. This decline could be attributed to several environmental or ecological factors, including shifts in local food availability, changes in climate conditions, and

potential alterations in habitat structure. These temporal declines observed in 2022, particularly in *T. sessile* and *A. cerana indica*, might also reflect changes in environmental factors such as temperature fluctuations, which can have a direct impact on pollinator foraging success (Kamaraj & Rasappan, 2024; Anandhabhairavi *et al.*, 2020; Usha & Devi, 2020; Bhagawati *et al.*, 2016). Notably, *Apis cerana indica* exhibited a decrease in visitation from 17.63 visits per 2 hours in 2021 to 15.40 visits per 2 hours in 2022, while bat also showed a slight decline in activity, which may point to potential habitat shifts or changes in food resource availability (Fill *et al.*, 2022; Sharma *et al.*, 2021; Baskaran & Thiyagesan, 2013; Wolcott & Vulinec, 2012; Haq *et al.*, 2010).

Further analysis using Spearman's rank correlation coefficients revealed that temperature at 2 meters (TM) and dew point (TDEW) had positive correlations with several pollinator species, particularly *A. cerana indica*, which exhibited a significant positive correlation ($r_s = 0.802$, $p < 0.01$). These results align with findings by Coates *et al.* (2024); Descamps *et al.* (2021); Lee & Kang (2018); Rands & Whitney (2008) who highlighted the role of warmer temperatures in promoting increased pollinator activity. Conversely, the negative correlations observed between specific humidity (QV) and some species, such as *B. bicoloratus* ($r_s = -0.375$, $p < 0.01$), suggest that higher humidity might hinder certain species' foraging activities, as also noted in studies by Polatto & Junior (2022); Sahu *et al.* (2019), which examined the impact of environmental moisture levels on pollinator dynamics.

In addition to temperature and humidity, wind speed (WS) emerged as a significant factor influencing pollinator activity. High wind speeds negatively correlated with foraging behavior in species such as *B. bicoloratus* and *A. cerana indica*, a finding consistent with previous studies indicating that strong winds can impede the movement and foraging efficiency of pollinators (Hennessy *et al.*, 2021; Hennessy *et al.*, 2020; Lewis *et al.*, 2015). These findings emphasize the significance of moderate climatic conditions, such as balanced temperatures and low wind speeds, in maintaining optimal pollinator activity, which is crucial for ecosystem services like pollination.

The temporal shifts in visitation observed across the years, particularly the decline in early morning activity, may also be indicative of broader ecological or environmental changes. These shifts could be linked to altered phenological patterns of flowering plants or changes in local biodiversity driven by climate change (Tsuzuki & Ohara, 2022; Wang *et al.*, 2021; Xu *et al.*, 2021; Kehrberger & Holzschuh, 2019). Moreover, species such as *Vespa affinis* and *Trigona* spp., which exhibited consistent diurnal foraging behavior, may be more resilient to such changes, while species like *Achaea serva* and *Eudocima phalonia*, with more pronounced nocturnal foraging patterns, are more susceptible to fluctuations in environmental factors such as light and temperature (Buddendorf *et al.*, 2025; Wong & Didham, 2024; Hakami *et al.*, 2020; Owens & Lewis, 2018). The observed patterns highlight the need for ongoing research into how climate induced changes in temperature and precipitation regimes may impact pollinator communities, particularly those with specialized foraging behaviors.

Despite the observed declines in visitation frequency in 2022, Hymenoptera (including *Apis cerana indica* and *Bombus bicoloratus*) continued to be the dominant group in terms of visitation frequency, followed by Chiroptera (bats) and Formicidae (ants), supporting the critical role of these taxa in maintaining pollination services. Recent research confirms global declines in pollinator species due to multiple drivers, including habitat loss, land-use intensification, climate change, pesticide exposure, and ecological shifts in local environments. This decline is linked to both reduced visitation rates and measurable drops in plant reproductive success (fruit set, seed set, and overall yield) (Hanberry, 2025; Artamendi *et al.*, 2025; Lee *et al.*, 2024). Native and wild pollinators, not just managed bees, are crucial for sustainable crop production and ecological resilience, accentuating the need for habitat restoration and better land management practices. The slight reduction in visitation by bats and *Apis cerana indica* further emphasizes the need for a deeper understanding of the environmental factors that drive these temporal shifts in pollinator behavior and the potential long-term consequences for biodiversity and food security.

6.5. Mating system dynamics

The present study analyzed fruit formation in relation to four primary mating systems : autogamy, open pollination, geitonogamy, and xenogamy, across three consecutive years (2021-2023), providing a comprehensive evaluation of how these reproductive strategies influence reproductive success. Notably, autogamous self-pollination resulted in a complete absence of fruit formation (0%) in all years, underscoring the inefficacy of this mechanism for the studied species. This outcome suggests a strong degree of self-incompatibility or possible structural barriers to effective self-fertilization, phenomena that have been similarly documented in other self-incompatible or obligately outcrossing taxa (Han *et al.*, 2025; Barreda-Castillo *et al.*, 2024; Surina *et al.*, 2024).

In contrast, open pollination reliant upon biotic vectors such as insects showed consistently high and increasing fruit set rates, rising from 72.67% in 2021 to 90.67% in 2023. This upward trend, coupled with reduced year-to-year variability, highlights the essential and increasingly stable contribution of natural pollinators in sustaining the reproductive output of the species, corroborating recent findings in both crop and wild plant systems that underscore the pivotal role of pollinator diversity in ensuring yield stability and fruit quality (Ma *et al.*, 2025; Zhang *et al.*, 2022). The escalating efficacy of open pollination observed in this study may be attributable to improvements in pollinator abundance, adaptation of floral traits, or favorable environmental conditions, each of which warrants further mechanistic investigation (Surina *et al.*, 2024; Tanaka & Wada, 2022).

Geitonogamy, involving pollination between flowers of the same individual, yielded moderate but progressively increasing fruit formation percentages (from 14.67% in 2021 to 33.33% in 2023). Though geitonogamy was markedly less effective than open pollination, its rising contribution may reflect dynamic responses to intra-plant pollen transfer or alterations in pollinator foraging behavior, in line with reports that geitonogamy can serve as a reproductive assurance mechanism when cross-pollination is limited (Muñoz-Gallego *et al.*, 2025; Trueman *et al.*, 2025). However, the lower and more variable fruit set associated with geitonogamy relative to open pollination

suggests its secondary supportive role in reproductive assurance rather than as a primary driver of fruit production.

Xenogamy, or cross-pollination between individuals, also exhibited a gradual enhancement in fruit formation across the three-year study period (from 19.33% to 38.00%). The increasing success rate of xenogamy is consistent with the evolutionary advantage of outcrossing, which promotes greater genetic diversity and seed vigor traits well-documented in contemporary pollination biology literature for optimizing progeny fitness and population resilience (Sagili *et al.*, 2025; Barreda-Castillo *et al.*, 2024; Surina *et al.*, 2024; Karron *et al.*, 2012). Nevertheless, similar to geitonogamy, fruit set through xenogamy was characterized by relatively higher variability, further indicating environmental stochasticity or pollinator-related constraints.

Together, these findings affirm the superiority of open pollination in maximizing fruit set, providing strong empirical support for the importance of biodiversity and functional pollinator guilds in ecosystem and agroecosystem resilience (Sagili *et al.*, 2025; Ma *et al.*, 2025). The observed incremental gains in fruit set via geitonogamy and xenogamy over time may point to ongoing ecological shifts perhaps due to fluctuations in pollinator populations, floral resource availability, or climate variables that could affect mating system dynamics at the population level (Muñoz-Gallego *et al.*, 2025; Surina *et al.*, 2024; Hada, 2024).

This investigation advances current understanding by demonstrating that, for the studied species, successful fruit formation depends overwhelmingly on external pollinators, with self-pollination mechanisms playing a negligible role. These results have significant implications for both conservation and agronomic management: optimizing habitat for diverse pollinators and maintaining genetic diversity through cross-pollination should be prioritized to ensure robust yield and population persistence under ongoing environmental changes. Targeted strategies might include enhancing pollinator habitats, sustaining floral resource diversity, and cultivating genotypes with flexible reproductive traits. Future studies should further dissect the ecological and molecular underpinnings of variable pollination success, particularly considering the interaction between biotic and abiotic determinants of mating system

efficacy (Seo *et al.*, 2025; Sagili *et al.*, 2025; Han *et al.*, 2025; Ma *et al.*, 2025; ; Surina *et al.*, 2024; Tanaka & Wada, 2022).

6.6. Role of diurnal and nocturnal pollinators in the reproductive success of *P. timoriana*

The reproductive success of *P. timoriana* is closely linked to the combined activity of nocturnal and diurnal pollinators, as revealed by differences in pod production and seed characteristics under varying pollination treatments. Pollinator exclusion resulted in no pod formation, establishing that *P. timoriana* is fully dependent on biotic pollination rather than autonomous self-fertilization a finding well supported by recent syntheses on the reliance of many flowering plants on animal pollinators for reproductive success (Rahimi & Jung, 2025; Kalpana *et al.*, 2024). Open pollination, incorporating both nocturnal and diurnal visitors, resulted in the highest pod set, seed number, and seed quality, underscoring the importance of diverse pollinator communities for maximizing reproductive output (Kendall & Nicholson, 2025; Katumo *et al.*, 2022).

Contemporary research has confirmed the value of complementary activity across the diel cycle. For instance, a global meta-analysis described how both diurnal and nocturnal pollinators enhance reproductive success through diel complementarity, challenging outdated expectations of daytime pollination dominance and reinforcing the need for conserving both pollinator groups in ecological networks. Studies focusing specifically on tropical and subtropical plants consistently report that exclusion of either pollinator guild leads to measurable reductions in seed set, pod formation, or seed quality, highlighting their distinct but complementary roles (Dzul-Cauich & Munguía-Rosas, 2025; Singh *et al.*, 2024; Jaeger *et al.*, 2023). Nocturnal pollination alone in this system produced pod and seed traits nearly equal to open pollination reflecting findings that nocturnal pollinators such as bats and moths often facilitate long-distance pollen dispersal and thus support genetic connectivity (Barbot *et al.*, 2025; Singh *et al.*, 2024; Teng *et al.*, 2024). These results are consistent with observed patterns in other tropical legumes and tree bean analogs, where nocturnal pollinator exclusion significantly reduces reproductive output (Singh *et al.*, 2024).

In contrast, diurnal pollination of *P. timoriana* resulted in markedly reduced pod and seed parameters, including a >80% reduction in pod number per capitulum and a 20% drop in average seed weight. These results mirror new empirical evidence that the effectiveness of pollination in the daytime may be limited by pollinator foraging behavior, time constraints, or temperature-dependent activity patterns (Dzul-Cauich & Munguía-Rosas, 2025; Jaeger *et al.*, 2023). Nonetheless, diurnal pollinators still contribute to viable seed production, supporting the concept that redundancy between pollinator guilds can buffer plants against temporal gaps in visitation (Teng *et al.*, 2024; Katumo *et al.*, 2022).

Recent advances in network ecology also demonstrate that integrating both diurnal and nocturnal pollinator data into plant-pollinator networks increases network complexity, connectivity, and resilience (Teng *et al.*, 2024). Notably, network-level studies indicate that nocturnal pollinators tend to have more specialized interactions, while diurnal pollinators often act as generalists together safeguarding the stability of plant reproductive systems against environmental change (Kendall & Nicholson, 2025; Teng *et al.*, 2024; Katumo *et al.*, 2022).

Correlation analyses in the present results reveal important reproductive trait dynamics. The positive relationships between seed number, pod set, seed length, and weight support the hypothesis that effective pollination benefits both seed quantity and quality, while negative size number correlations highlight classic resource allocation trade-offs (Barbot *et al.*, 2025; Kalpana *et al.*, 2024; Katumo *et al.*, 2022). These relationships have wide ecological and evolutionary implications, affecting offspring fitness, population structure, and the evolutionary trajectory of breeding systems.

Given recent reports of pollinator declines due to habitat loss, climate change, and pesticide use, maintaining both diurnal and nocturnal pollinator assemblages is critical for sustaining the reproductive viability of tropical keystone species like *P. timoriana* (Rahimi & Jung, 2025; Kalpana *et al.*, 2024; Otieno & Namiripo, 2020). Future research should incorporate long-term monitoring and multi-taxa experimental approaches to further clarify the mechanistic basis of pollination resilience and inform integrated conservation policy (Rahimi & Jung, 2025; Rueda-Uribe *et al.*, 2025).

6.7. Spatiotemporal dynamics of pollen production and floral traits

The present analysis provides insights into the spatiotemporal dynamics of pollen production, pollen-ovule (P/O) ratio, and associated floral traits across three altitudinally distinct sites (Sairang, Tanhril, and Reiek) from 2021 to 2023. The observed patterns underscore the complex interplay between environmental gradients, plant reproductive biology, and climate variability, alongside the importance of sustained pollinator interactions.

Significant differences were detected in inflorescence number, flower output, and nectar-producing floral structures among sites and across years. Notably, Tanhril and Reiek positioned at mid and high elevations frequently exhibited elevated reproductive metrics compared to the lower site, Sairang. These findings corroborate recent observations that environmental factors associated with elevation, such as temperature regime and pollinator composition, exert a strong influence on plant reproductive success and floral trait allocation (Shrestha *et al.*, 2024; Wang *et al.*, 2024; Hasegawa *et al.*, 2023). For instance, some alpine flora demonstrate a trade-off where flower size increases but number declines with altitude, an adaptive mechanism linked to resource allocation and climate resilience (Shrestha *et al.*, 2024; Wang *et al.*, 2024).

Yearly fluctuations in pollen per anther and per flower most pronounced as dips in 2022 with subsequent recovery by 2023 suggest a plastic response to interannual environmental variability, likely reflecting the impact of temperature anomalies or altered rainfall on gametophyte development (Mousavi *et al.*, 2024; Ranpal *et al.*, 2023). However, stable floral structural traits, such as anther number per flower, indicate underlying genetic canalization, echoing research in which core reproductive morphological features remained unaffected by environmental gradients (Wang *et al.*, 2024).

Pollen productivity was generally greatest at Reiek and Tanhril and displayed patterns congruent with mean flower and nectar-secreting flower production, showing site-specific resilience following environmental fluctuations. While a decline was observed in 2022, the robust rebound in 2023 aligns with models predicting that plant reproductive traits in high-altitude or climate-variable ecosystems can recover rapidly

under favorable conditions, presumably due to factors such as stored carbohydrate reserves and adaptive pollinator foraging behavior (Mousavi *et al.*, 2024; Zhang & Steiner, 2022). Pollen output, especially per inflorescence and per tree, also paralleled altitudinal and temporal trends, supporting the hypothesis that both ecological context and microclimate can modulate reproductive capacity over short timescales (Anjum *et al.*, 2025; Wang *et al.*, 2024; Hasegawa *et al.*, 2023).

The abundance of ovules per flower across sites and years remained relatively stable or recovered quickly after transient declines, indicating a conservative female reproductive investment in these populations. This stability is reflected in the calculated pollen-ovule (P/O) ratios, which remained statistically consistent across all sites, aligning with contemporary findings that species with such intermediate ratios are typically outcrossing, relying on both biotic pollinators and some degree of reproductive flexibility (Harder *et al.*, 2023; Wang *et al.*, 2004; Cruden, 1977). While the pollen-ovule ratio remains a widely referenced indicator of plant mating systems, recent work cautions that its interpretation should be contextualized within each species' ecological and evolutionary setting (Harder *et al.*, 2023; Cruden, 1977).

Importantly, correlation analyses revealed strong positive associations between total flower production and both hermaphrodite flower and pollen output at all sites. Such correlations reinforce the concept that increased floral display can drive greater pollen production, enhancing the likelihood of reproductive success and efficient pollinator visitation (Koski, 2023; Eilers *et al.*, 2021; Jiao *et al.*, 2021). At the same time, elevated sites such as Reiek, with more stable and abundant floral/P/O traits, suggest that high-altitude environments may buffer reproductive investment against climate-driven perturbations (Anjum *et al.*, 2025; Shrestha *et al.*, 2024; Wang *et al.*, 2024).

Overall, these findings highlight that plant reproductive strategies in montane environments are shaped by a delicate balance between genetic constraints, environmental pressures, and pollinator availability. The resilience and plasticity observed in floral and pollen output across altitudinal gradients and years not only provide insight into species' evolutionary adaptability but also serve as critical empirical evidence for predicting how plant populations may respond to ongoing

climate change. Further research integrating fine-scale climatic data, pollinator assemblage shifts, and long-term reproductive monitoring will be essential for contextualizing these patterns (Anjum *et al.*, 2025; Wang *et al.*, 2024; Ranpal *et al.*, 2023; Hasegawa *et al.*, 2023; Zhang & Steiner, 2022).

6.8. Temporal variability in pollen concentrations

Understanding the temporal dynamics of airborne pollen dispersal plays a pivotal role in comprehending plant reproductive biology, pollination ecology, and ecological forecasting, especially amidst rapidly changing climatic conditions. The present investigation provides detailed insights into the diurnal fluctuations of airborne pollen density, with clear evidence for pronounced temporal variability modulated by prevailing meteorological conditions. Both the slide hanging method and the GRIPS-99M Rotation Impaction Sampler revealed that pollen concentrations peak during the early morning hours and decline during the remainder of the day. Specifically, the slide method recorded a maximum pollen concentration of $340.82 \pm 52.60\text{cm}^2$ between 05:00 and 06:00hr, while the impaction sampler showed a peak of $200.57 \pm 34.16\text{m}^3$ from 04:00 to 05:00hr. These trends closely mirror findings in current aerobiological research, which identify cooler nocturnal and early morning periods as critical windows for maximal pollen release and atmospheric dispersal due to optimal interactions of temperature, humidity, and wind (Frisk *et al.*, 2023; Ščevková *et al.*, 2023; Goudarzi *et al.*, 2022).

The subsequent decline in pollen levels through late morning, afternoon, and evening likely corresponds with rising temperatures and increased solar radiation, both of which are known to accelerate pollen desiccation and decrease atmospheric stability, limiting particle suspension (Frisk *et al.*, 2023; Zhang & Steiner, 2022; Chatkin *et al.*, 2022). Such diurnal patterns are consistent with models demonstrating strong sensitivity of pollen emission and dispersal to both temperature and humidity, where higher ambient temperatures can precipitate a reduction in airborne pollen counts, and increased relative humidity acts to facilitate both pollen release from anthers and prolonged suspension in the air column (Humayun *et al.*, 2025; Frisk *et al.*, 2023; Ščevková *et al.*, 2023).

Correlation analysis in this study further highlighted that increases in temperature, specific humidity, dew point, and photosynthetically active radiation (PAR) correspond with marked reductions in pollen density, while relative humidity and moderate wind speeds have a complementary positive association (Ščevková *et al.*, 2023; Zhang & Steiner, 2022; Goudarzi *et al.*, 2022). These results reinforce the notion that pollen dispersal is not simply passive but is dynamically regulated by a suite of environmental drivers interacting on daily and seasonal timescales (Zhang & Steiner, 2022; Chatkin *et al.*, 2022; Skjøth *et al.*, 2021). The robust agreement between volumetric and gravimetric sampling methods further validates these findings and supports their reliability for both ecological investigations and real-time allergen forecasting applications.

This study underscores the urgent need for integrated environmental monitoring and model development, especially as climate variability continues to alter pollen emission periods, atmospheric composition, and broad-scale ecosystem phenology (Sofiev *et al.*, 2023; Zhang & Steiner, 2022). Accurate, temporally resolved pollen modeling is of direct relevance for public health management, particularly for developing adaptive strategies to mitigate the impact of exposure for allergy sufferers during peak dispersal periods (Sofiev *et al.*, 2023; Chatkin *et al.*, 2022).

6.9. Evaluating pollen viability in floral morphs

The comparative evaluation of pollen viability between hermaphrodite and nectar-secreting flowers using TTC (2,3,5-triphenyl tetrazolium chloride), FDA (fluorescein diacetate), and Alexander staining elucidates key differences both in the efficacy of staining techniques and in the physiological status of pollen among floral types. The highest pollen viability estimates were consistently observed with the Alexander staining method, followed by FDA and then TTC, in both hermaphrodite and nectar-secreting flowers. Specifically, the Alexander method yielded viability values of 77.17% for hermaphrodite flowers and 60.48% for nectar-secreting flowers, FDA produced intermediate values (73.82% and 50.39%, respectively), while TTC generated the lowest estimates (60.35% and 44.32%). These statistically significant differences ($p < 0.01$) highlight that the methodology employed can substantially

influence perceived pollen viability, a trend corroborated by recent literature which suggests variable sensitivity and specificity among staining protocols (Kanneri *et al.*, 2025; Li *et al.*, 2023; Impe *et al.*, 2020).

Recent findings indicate that FDA, a metabolic stain detecting esterase activity and membrane integrity, is generally regarded for its accuracy and is widely employed due to strong correlation with *in vitro* germination (Kasthuriangan *et al.*, 2025; Li *et al.*, 2023; Impe *et al.*, 2020). However, the Alexander staining method, which assesses cytoplasmic integrity, often yields higher viability rates, possibly due to its ability to stain aborted but cytoplasmically intact pollen, potentially leading to overestimation of viability, as noted in wheat and other species (Impe *et al.*, 2020). Despite this limitation, our results align with previous studies reporting highest viability percentages with Alexander staining, similar to findings in *Gleditsia sinensis* and wheat (Kanneri *et al.*, 2025; Impe *et al.*, 2020). In contrast, TTC, which relies on dehydrogenase activity, often returns the lowest viability rates, which may reflect its limited applicability to certain taxa or developmental stages (Kılıç *et al.*, 2024; Li *et al.*, 2023).

The substantial and consistent differences in viability percentages between hermaphrodite and nectar-secreting flowers observed across all three staining methods underscore the functional divergence between these two floral morphs. Hermaphrodite flowers exhibited distinctly higher pollen viability under all staining protocols. This higher viability could reflect differences in resource allocation, floral physiology, and reproductive strategy. Studies in gynodioecious and andromonoecious systems reveal that hermaphrodite or male-biased flowers frequently allocate more resources to gamete viability, resulting in higher reproductive potential and more effective recruitment during pollination events (Sanchez *et al.*, 2024; Varga *et al.*, 2013).

Variation in standard deviation among methods was most pronounced for Alexander staining in hermaphrodite flowers, possibly due to the inclusion of aborted yet cytoplasmically intact grains artificially inflating variability (Kanneri *et al.*, 2025; Impe *et al.*, 2020). Such methodological variance should be carefully considered in

practical applications, particularly when high precision in pollen viability measurement is required for breeding or fertility studies.

Furthermore, the differential pollen viability documented between hermaphrodite and nectar-secreting flowers has direct biological implications. Higher pollen viability in hermaphrodite flowers may contribute to greater male reproductive success and enhanced gene flow, while the lower viability in nectar-secreting flowers may reflect a reallocation of resources toward reward production rather than pollen function (Sanchez *et al.*, 2024; Varga *et al.*, 2013). This partitioning of function is consistent with resource allocation theories and may influence pollinator behavior, mating system evolution, and overall reproductive fitness within and among species.

Our findings reinforce the critical importance of methodological choice in pollen viability assessment and provide new evidence for floral type-specific differences in pollen viability that are consistent across cytochemical and metabolic assays. These data have implications for the understanding of reproductive biology and can inform strategies in plant breeding and genetic conservation by aligning method selection with specific research objectives (Stokes & Geitmann, 2025; Kasthuriangan *et al.*, 2025; Kanneri *et al.*, 2025; Li *et al.*, 2023; Impe *et al.*, 2020).

6.10. Nectar secretion dynamics in *P. timoriana*

The temporal dynamics of nectar secretion in *P. timoriana* revealed pronounced nocturnal patterns, aligning with findings in other night-flowering and tropical species. Nectar concentrations peaked at the onset of the evening, gradually declining through the night and reaching their lowest values by early morning. This diurnal oscillation of nectar concentration and volume reflects the plant's adaptive strategy to maximize pollinator visitation during favorable environmental windows primarily in the early evening when pollinators are most active before physiological and environmental constraints, such as temperature drops and reduced humidity, curb nectar secretion rates (Tiedge & Lohaus, 2018; Heil *et al.*, 2000). The observed stability in nectar secretion within specific time blocks, evidenced by low standard deviations, points to an intrinsic circadian regulation that is relatively resilient to microenvironmental

fluctuations, a phenomenon documented across multiple taxa (Chen *et al.*, 2025; Tiedge & Lohaus, 2018).

The hourly measurements of nectar sugar content further substantiated the existence of a clear nocturnal secretion rhythm. The rapid decline in sugar concentration from the evening peak likely results from metabolically mediated resource allocation coupled with the incremental demands placed by pollinator foraging activity (Maldonado *et al.*, 2023; Tiedge & Lohaus, 2018). Stable sugar levels during the late evening could represent an ecological compromise, ensuring continued pollinator attraction as night progresses. This is consistent with the behavior of several nocturnal and crepuscular pollinators, which rely on a sustained, not merely maximal, nectar reward for foraging optimization (Tiedge & Lohaus, 2018; Farkas *et al.*, 2012). The association between time-dependent nectar depletion and pollinator behavior underlines the ecological significance of nectar secretion telemetry in shaping mutualistic plant-pollinator interactions (Maldonado *et al.*, 2023).

In terms of nectar energetics, the decreasing energy values throughout the night provide a quantitative foundation for understanding pollinator foraging preferences and temporal partitioning. The high energy content during the evening may serve as a pollinator “magnet,” increasing plant reproductive success through enhanced cross-pollination when both resource and demand are high (Maldonado *et al.*, 2023). As energy availability wanes, a corresponding reduction in pollinator visitation is anticipated, as evidenced in analogous nocturnal systems.

Daily nectar production per inflorescence showed modest variation through the observation period. Such stability in daily output, despite hourly oscillations, suggests a strong underlying physiological regulation of nectar secretion, likely shaped by evolutionary pressures to maintain reliable signals for pollinators and maximize reproductive assurance (Maldonado *et al.*, 2023; Parachnowitsch *et al.*, 2019). Consistent daily yields are regarded as a crucial determinant for plant fitness in stochastic environments, improving pollinator constancy throughout the flowering period (Parachnowitsch *et al.*, 2019; Farkas *et al.*, 2012).

Analysis of the nectar's biochemical composition, particularly sugars and amino acids, elucidated its nutritional provisioning to pollinators. The predominance of sucrose is notable, marking *P. timoriana* nectar as especially attractive to bee species, which often exhibit a sucrose preference. Meanwhile, the presence and diversity of amino acids, including glutamine, asparagine, and aspartic acid, are consistent with profiles observed in other angiosperms, often reflecting both phylogenetic and pollinator-driven selection (Göttlinger & Lohaus, 2023; Nicolson, 2022). Amino acids, though present at orders of magnitude lower concentrations than sugars, can significantly impact pollinator health, learning, and behavior, with species-specific preferences for particular amino acids influencing floral choice and subsequently reproductive isolation and specialization (Göttlinger & Lohaus, 2023; Nicolson, 2022).

Environmental correlation analysis demonstrated that nectar quantity, concentration, and energetics are negatively associated with time, echoing trends seen under diurnal/nocturnal regulation in other species (Heil *et al.*, 2000). Notably, positive associations with temperature, dew point, wet bulb temperature, and specific humidity suggest that both thermal and hydric conditions favor increased nectar secretion, while minimal effects from relative humidity and precipitation are in accordance with multifactorial models of nectar dynamics (Bodó *et al.*, 2021; Chabert *et al.*, 2020; Takkis *et al.*, 2018). Soil moisture emerged as a significant factor linked to daily nectar yield, corroborating findings that soil parameters can influence both the frequency of nectar-producing flowers and nectar volume (Cha *et al.*, 2025; Bodó *et al.*, 2021). The negative effect of wind speed on nectar collection is likely attributable to increased evapotranspiration and physical removal of nectar, as well as potential pollinator deterrence.

Collectively, these findings highlight the complex interplay between plant physiology, nectar composition, pollinator ecology, and abiotic environmental variables in shaping the spatiotemporal patterns of nectar availability (Roguz *et al.*, 2025; Chabert *et al.*, 2020; Parachnowitsch *et al.*, 2019). This multifactorial regulation of nectar traits underscores the need for integrative approaches in nectar ecology research, emphasizing the importance of both intrinsic plant mechanisms and extrinsic environmental factors in determining ecosystem-level pollination dynamics. Such

knowledge is critical, especially in the context of ongoing climate change, which may alter the phenology and quantitative parameters of floral rewards, with far-reaching consequences for plant-pollinator networks (Parachnowitsch *et al.*, 2019; Takkis *et al.*, 2018).

6.11. Optimizing *in vitro* pollen germination

The present study provides comprehensive insights into the factors governing *in vitro* pollen germination, emphasizing the complex interplay of sucrose concentration, plant growth regulators, temperature, and incubation time. The results corroborate and expand upon recent discoveries in the field, offering valuable implications for optimizing *in vitro* fertilization protocols for plant breeding and biotechnology.

Sucrose plays a pivotal role in pollen germination by serving as both an energy source and osmoregulatory agent. Our findings demonstrated negligible pollen germination in distilled water, while increasing sucrose concentrations (particularly 15% and 20%) substantially enhanced pollen germination. This effect was most pronounced at 24 hours and declined at subsequent time points, in alignment with previous studies that identified optimal sucrose concentrations and demonstrated that both insufficient and excessive sucrose can be detrimental to pollen viability (Seitz *et al.*, 2023; Fragallah *et al.*, 2019; Brewbaker & Kwack, 1963). The time-dependent attenuation in germination supports the view that pollen metabolic activity, viability, and sucrose transporter function decrease over extended *in vitro* culture, emphasizing the importance of both concentration and exposure duration in pollen germination assays (Seitz *et al.*, 2023; Fragallah *et al.*, 2019).

Supplementation with IAA significantly improved germination rates, with an optimal effect observed at 50 ppm during the initial 24-hour incubation. The stimulatory effect of IAA diminished over time, reflecting previous reports that auxin-mediated cell wall loosening and H⁺-ATPase activation facilitate rapid but short-lived pollen tube growth (Kumar *et al.*, 2016; Wu *et al.*, 2008). The pronounced initial response, followed by a decline in efficacy, suggests that IAA may promote germination primarily through early metabolic activation and pollen tube out growth (Kumar *et al.*, 2016; Wu *et al.*, 2008).

Similarly, IBA promoted pollen germination in a concentration-dependent manner, peaking at 100 ppm during the first 24 hours before declining over time. IBA, like IAA, acts primarily as a rooting hormone but also participates in modulating cell elongation and division within pollen tubes (Lesmes-Vesga *et al.*, 2021; Schlicht *et al.*, 2013). The present results suggest that IBA's effect, although potent, is transient, emphasizing the necessity for precise timing in applications targeting pollen embryo rescue or somatic embryogenesis.

Kinetin at intermediate concentrations (20–50 ppm) enhanced pollen germination, whereas lower and higher concentrations were less effective. This hormetic response is consistent with published data showing that low concentrations of kinetin favorably affect both germination and pollen tube elongation in several species (Hamad *et al.*, 2023; Maita & Sotomayor, 2015). As with the auxins, the benefit was strongest during early incubation, indicating kinetin's potential role in modulating cytokinin signaling during pollen activation (Hamad *et al.*, 2023; Kumar *et al.*, 2016; Maita & Sotomayor, 2015).

GA₃ supplementation markedly enhanced pollen germination, particularly at 50–100 ppm, with the maximum effect at 24 hours and a gradual reduction thereafter. This trend is supported by previous research showing that GA₃ promotes pollen germination and tube growth through upregulation of amylase activity and mobilization of stored polysaccharides, crucial for rapid pollen tube elongation (Kumar *et al.*, 2016; Voyiatzis & Paraskevopoulou-Paroussi, 2000). Higher concentrations of GA₃, while stimulatory, can also trigger feedback inhibition if exposure is prolonged or excessive (Voyiatzis & Paraskevopoulou-Paroussi, 2000).

When comparing different plant growth regulators, IBA and GA₃ (especially at 100 ppm) demonstrated the greatest efficacy in promoting pollen germination, followed by IAA and kinetin. These findings align with the broader literature, which consistently emphasizes the importance of auxins and gibberellins in gametophytic cell expansion and fertilization success (Hamad *et al.*, 2023; Lesmes-Vesga *et al.*, 2021; Maita & Sotomayor, 2015).

Spearman's rank correlation analysis revealed strong positive correlations between concentration and successful pollen germination for IAA, IBA, GA₃, and sucrose, with the strongest associations observed for IBA and GA₃. In contrast, incubation time showed significant negative correlations with all tested variables, confirming that prolonged exposure reduces overall germination efficiency. The robust positive inter-correlations among the major plant hormones highlight their overlapping and potentially synergistic roles in pollen activation and tube growth (Kumar *et al.*, 2016; Maita & Sotomayor, 2015; Schlicht *et al.*, 2013; Wu *et al.*, 2008).

Temperature exerts a profound influence on both pollen germination and tube growth, with significant implications for plant reproductive biology and applied breeding programs. The data clearly demonstrate that *in vitro* pollen germination is maximized at 25°C, with an average success rate approaching 90%, while both cooler (15°C) and warmer (30°C) regimes result in marked reductions in germination efficiency. This response highlights the existence of a thermal optimum for pollen function, corroborating and extending observations in diverse taxa that reproductive performance is highly sensitive to thermal cues, particularly during the gametophytic phase (Hedhly, 2011). The decline in germination at suboptimal temperatures may reflect impaired metabolic activity and enzymatic processes essential for pollen hydration and tube emergence, phenomena previously documented in both model and crop systems (Bita & Gerats, 2013).

Similarly, pollen tube elongation exhibited a pronounced peak at 25°C, with average tube lengths notably longer than at adjacent temperature points. The sharp reduction in tube length at 30°C despite relatively higher germination compared to 15°C suggests that supra optimal temperatures more strongly affect post-germination growth dynamics than the initial germination process. Temperature dependent pollen tube elongation is crucial for successful fertilization and has been shown to be mediated by cellular membrane stability, cytoskeletal rearrangements, and regulated calcium ion flux, all of which are highly susceptible to thermal disruption (Cheung *et al.*, 2008). The statistically significant, moderately positive correlations observed between temperature and both pollen germination and tube length reinforce the notion that these traits are co-regulated by the thermal environment, with both processes benefiting from

conditions near the optimum. Most notably, the very strong positive correlation between pollen germination and pollen tube length underscores that successful germination is directly linked to robust pollen tube growth, highlighting the sequential dependency of fertilization processes (Liu *et al.*, 2024; Zhang *et al.*, 2023). These results are consistent with the broader literature emphasizing the impact of environmental variables chiefly temperature on plant fertility, as demonstrated across a range of angiosperms including economically significant crops (Janni *et al.*, 2024; Hatfield & Prueger, 2015; De Storme & Geelen, 2014).

CHAPTER 7

SUMMARY AND CONCLUSION

The present study offers a comprehensive multi-year, multi-site assessment of the reproductive biology and ecology of *P. timoriana*, examining its phenological patterns, floral biology, pollinator interactions, reproductive success, and the influence of environmental variables across altitudinal gradients in the Indo-Burma biodiversity hotspot. Central to this investigation was the elucidation of how both abiotic factors such as temperature fluctuations, specific and relative humidity gradients, soil moisture variability, wind dynamics, and photosynthetically active radiation and biotic components, including a diverse community of pollinator taxa ranging from Hymenoptera (bees and ants) to Chiroptera (bats), shape the reproductive phenology, mating systems, and ultimately, the reproductive fitness of this ecologically important tropical tree species. These findings deepen the understanding of tropical reproductive ecology by linking fine scale climatic variability with detailed floral and pollinator trait data. Importantly, the research addresses conservation relevant issues by demonstrating how elevation related microclimatic buffering modulates reproductive timing and pollinator activity, supporting predictive frameworks for biodiversity resilience amid accelerating climate change. The integration of biochemical nectar profiles, pollen viability assays, and *in vitro* germination experiments bridges ecological observation with reproductive physiology, highlighting the multi-dimensional nature of plant reproductive success.

Monitoring of reproductive phenology over three years elucidated significant spatial and temporal variation linked to site-specific environmental conditions, especially elevation and local climatic parameters. The documented delays in flowering onset at the lowest elevation site (Sairang) coincide with increasing local temperatures and humidity shifts, likely impacting floral developmental cues and resource allocation strategies. At the mid- and high-elevation sites (Tanhiril and Reiek), phenological

stability suggests a climate buffering effect, consistent with montane ecosystem resilience hypotheses. Analysis of flowering duration revealed contrasting trends: an overall extension at Sairang may reflect adaptive plasticity to elongated growing seasons, while contraction at higher elevations aligns with temperature-limited growing periods. These patterns corroborate global meta-analyses confirming elevation-dependence of phenological shifts in tropical trees. Peak flowering timing fluctuations further illustrate phenological lags modulated by altitudinal microclimates. The increased amplitude and flowering synchrony observed at certain sites intimate compensation mechanisms enhancing pollination efficiency despite phenological delays. The complex, often stage-dependent correlations between temperature, humidity, precipitation, wind, and phenological events underscore a nuanced reproductive response framework. Such responsiveness implies potential thresholds beyond which reproductive success may sharply decline, a crucial consideration for conservation under climate projections predicting increased temperature extremes and altered precipitation regimes.

The floral biology of *P. timoriana* demonstrates a complex interplay of morphological traits and ecological interactions critical for successful pollen transfer and fertilization. Synchronization of anthesis with pollinator activity, peaking between 17:00 and 19:00, offers temporal optimization for attracting both diurnal and nocturnal pollinators, thereby maximizing reproductive assurance in habitats experiencing phenological variability. The rapid, asynchronous opening of flowers within inflorescences promotes both outcrossing potential and genetic diversity. Protandry and tight synchronization of anther dehiscence with anthesis reduce self-fertilization risk and enhance cross-pollination efficacy. The adaptation of floral morphology, including tightly packed polyads, ensures efficient pollen dispersal while minimizing loss, particularly important for a species relying on animal vectors with varying foraging behaviors. Detailed enzymatic assessment of stigma receptivity highlights the temporal window for successful fertilization and its sensitivity to environmental variables, including temperature and humidity. Collectively, these mechanisms exemplify evolutionary fine-tuning that balances resource investment with

reproductive payoff, supporting species persistence in complex tropical ecosystems subject to climatic oscillations.

Morphological analyses highlighted the structural organization of pollen into polyads of approximately 32 grains, an arrangement that enhances pollination efficiency by promoting cohesive dispersal. Variability in pollen metrics across sites and years reflected both genetic constants and plastic responses to environmental stressors, such as transient reductions in 2022 associated with anomalous climatic conditions. Stable attributes, e.g., constant anther number per flower, suggest genetic canalization, whereas pollen and flower production variances indicate adaptive flexibility potentially buffering reproductive success against environmental perturbation. These findings align with current understanding that reproductive traits exhibit both genetic determinism and phenotypic plasticity, enabling species to maintain fitness in fluctuating environments.

The comprehensive pollinator assessments reveal a diverse suite of diurnal and nocturnal taxa integral to *P. timoriana* reproductive success. Hymenoptera (especially *Apis cerana indica* and *Bombus bicoloratus*), Formicidae (ants), and Chiroptera (bats) constitute key biotic vectors, with temporal visitation patterns closely linked to floral phenology. The observed inter-annual decline in pollinator visitation, particularly during early morning and late-night periods in 2022, parallels global pollinator decline trends attributed to climate change, habitat fragmentation, and pesticide exposure. Positive correlations of pollinator activity with temperature and specific humidity but negative impacts from elevated wind speed suggest that both abiotic and biotic agents regulate pollination efficacy. The complementary roles of nocturnal and diurnal pollinators, evidenced by experimentally partitioned pollination treatments, emphasize the importance of conserving full pollinator guilds. These data contribute to ecological network theory, showing that interaction temporal partitioning enhances stability and resilience of pollinator services under environmental change.

Mating system investigations unequivocally demonstrated *P. timoriana*'s strict reliance on biotic cross-pollination for fruit set. The failure of autogamy across all experimental years indicates likely self-incompatibility or morphological barriers,

reinforcing obligate outcrossing status. Open pollination, incorporating the full spectrum of pollinators, yielded the highest fruit and seed quality, underscoring natural pollinator indispensability. The incremental yet secondary gains in fruit formation through geitonogamy and xenogamy suggest partial levels of reproductive assurance but highlight limitations relative to full biotic cross-pollination. These findings corroborate widespread ecological concepts associating pollinator diversity and network stability with reproductive success, particularly in tropical agroecosystems. The increasing success of cross-pollination modes over time may reflect dynamic ecological shifts or pollinator community changes, warranting further long-term monitoring.

Analyses of pollen viability and *in vitro* germination protocols provide foundational insights into reproductive physiology and practical breeding applications. The Alexander staining method consistently yielded the highest viability estimates, albeit with greater variability, suggesting its utility but also emphasizing potential for overestimation due to cytoplasmic integrity staining. Differential viability between hermaphrodite and nectar-secreting flowers supports resource allocation theories prioritizing male gamete fitness in hermaphrodites. Optimized germination conditions include sucrose concentrations around 15%, and hormonal supplementation with IBA and GA₃ at approximately 100 ppm, with 25°C identified as optimal temperature for both germination and pollen tube elongation. The declining germination efficiency over time highlights the importance of assay timing. These detailed physiological insights are critical for improving pollen-based technologies in conservation and crop improvement.

The nocturnal pulses of nectar secretion and its biochemical constituents reflect adaptive strategies for pollinator attraction and retention. Peak nectar concentration and energetic content at early evening coincide with peak pollinator activity, leveraging sucrose dominance favored by bees alongside a rich profile of amino acids, including glutamine, asparagine, and aspartic acid, which may modulate pollinator foraging preferences and fitness. Declining nectar quantity and energetics overnight may represent metabolic trade-offs or resource reallocation aligned with pollinator visitation patterns. Strong environmental correlations suggest that temperature, soil

moisture, and atmospheric humidity are key drivers of nectar traits, providing a mechanistic basis for predicting shifts in pollinator attraction under climate change scenarios. These findings reinforce the complexity of plant-pollinator mutualisms shaped by physiological and environmental variables.

Airborne pollen dispersal patterns exhibit marked diurnal fluctuations, with peak concentrations during pre-dawn and early morning periods characterized by cooler temperatures, higher relative humidity, and moderate wind speeds. This timing likely optimizes pollen viability and suspension, aligning with pollinator foraging windows and enhancing reproductive success. Negative correlations with temperature and photosynthetically active radiation reinforce the sensitivity of pollen dispersal to microclimatic conditions. Dual-method congruence of volumetric and gravimetric samplers ensures robust data validity. These patterns also have translational relevance for allergen forecasting and ecological monitoring, emphasizing the necessity for integrative environmental sensing to anticipate reproductive dynamics under rapidly changing climates.

Overall, this body of work highlights the intricate interplay among environmental factors, floral and pollen traits, pollinator dynamics, and reproductive strategies that collectively govern the reproductive success and ecological resilience of *P. timoriana*. The observed phenotypic plasticity and temporal dynamics reveal an adaptive capacity that may offer partial buffers against the increasing variability driven by global change. Nevertheless, documented declines in pollinator visitation and shifts in phenological timing raise concerns regarding the long-term stability of reproductive outcomes. These findings call for proactive conservation frameworks emphasizing pollinator guild protection, habitat heterogeneity maintenance, and landscape connectivity enhancement. The integration of physiological, ecological, and environmental data provides a comprehensive reference for both academic inquiry and practical conservation planning, emphasizing the need for multifaceted strategies to safeguard tropical biodiversity and ecosystem services.

Future research priorities should include expanded spatial and temporal monitoring to capture broader ecological heterogeneity and extreme climatic events; molecular

genomic studies to elucidate adaptive pathways linking phenology and fitness; and experimental assessments of pollinator-plant-climate interactions focusing on resilience mechanisms. The promotion of interdisciplinary approaches combining field ecology, physiological analysis, and modeling will be essential to advance predictive capabilities. In the context of accelerating environmental change, this research represents a timely contribution towards understanding and sustaining tropical agricultural and forest systems upon which millions depend.

REFERENCES

- Abdelgadir, H. A., Johnson, S. D., & Van Staden, J. (2012). Pollen viability, pollen germination and pollen tube growth in the biofuel seed crop *Jatropha curcas* (Euphorbiaceae). *South African Journal of Botany*, 79, 132-139. <https://doi.org/10.1016/j.sajb.2011.10.005>
- Acar, I., & Kakani, V. G. (2010). The effects of temperature on in vitro pollen germination and pollen tube growth of *Pistacia* spp. *Scientia Horticulturae*, 125(4), 569-572. <https://doi.org/10.1016/j.scienta.2010.04.040>
- Ackerman, J. D., & Roubik, D. W. (2012). Can extinction risk help explain plant–pollinator specificity among euglossine bee pollinated plants?. *Oikos*, 121(11), 1821-1827. <https://doi.org/10.1111/j.1600-0706.2011.20193.x>
- Adler, L. S., & Irwin, R. E. (2005). Ecological costs and benefits of defenses in nectar. *Ecology*, 86(11), 2968-2978. <https://doi.org/10.1890/05-0118>
- Aguilar, R., Ashworth, L., Galetto, L., & Aizen, M. A. (2006). Plant reproductive susceptibility to habitat fragmentation: review and synthesis through a meta-analysis. *Ecology Letters*, 9(8), 968-980. <https://doi.org/10.1111/j.1461-0248.2006.00927.x>
- Aizen, M. A., & Torres, A. (2024). The Invasion Ecology of Mutualism. *Annual Review of Ecology, Evolution, and Systematics*, 55. <https://doi.org/10.1146/annurev-ecolsys-102622-031210>
- Ajani, Y., & Claßen–Bockhoff, R. (2021). The unique inflorescence structure of *Dorema aucheri* (Apiaceae): An adaptation to the arid environment. *Journal of Arid Environments*, 184, 104194. <https://doi.org/10.1016/j.jaridenv.2020.104194>
- Alamgir, A. N. M. (2017). Cultivation of herbal drugs, biotechnology, and in vitro production of secondary metabolites, high-value medicinal plants, herbal wealth, and herbal trade. In: *Therapeutic Use of Medicinal Plants and Their Extracts: Volume 1: Pharmacognosy*, 379-452. Springer, Cham. https://doi.org/10.1007/978-3-319-63862-1_9
- Albano, S., Salvado, E., Borges, P. A., & Mexia, A. (2009). Floral visitors, their frequency, activity rate and Index of Visitation Rate in the strawberry fields of Ribatejo, Portugal: selection of potential pollinators. Part 1. *Advances in Horticultural Science*, 23(4), 238-245.
- Alcaraz, M. L., Montserrat, M., & Hormaza, J. I. (2011). In vitro pollen germination in avocado (*Persea americana* Mill.): Optimization of the method and effect of temperature. *Scientia Horticulturae*, 130(1), 152-156. <https://doi.org/10.1016/j.scienta.2011.06.030>

- Aleemullah, M., Haigh, A. M., & Holford, P. (2000). Anthesis, anther dehiscence, pistil receptivity and fruit development in the Longum group of *Capsicum annum*. *Australian Journal of Experimental Agriculture*, 40(5), 755-762. <https://doi.org/10.1071/EA99038>
- Alexander, M. P. (1969). Differential staining of aborted and nonaborted pollen. *Stain technology*, 44(3), 117-122. <https://doi.org/10.3109/10520296909063335>
- Allen-Perkins, A., Artamendi, M., Montoya, D., Rubio, E., & Magrach, A. (2024). Untangling the plant reproductive success of changing community composition and pollinator foraging choices. *Ecography*, e07240. <https://doi.org/10.1111/ecog.07240>
- Alqarni, A. S., Awad, A. M., Raweh, H. S. A., & Owayss, A. A. (2017). Pollination ecology of *Acacia gerrardii* Benth.(Fabaceae: Mimosoideae) under extremely hot-dry conditions. *Saudi Journal of Biological Sciences*, 24(7), 1741-1750. <https://doi.org/10.1016/j.sjbs.2015.09.019>
- Alquichire-Rojas, S., Escobedo, V. M., & González-Teuber, M. (2024). Impacts of increased temperatures on floral rewards and pollinator interactions: a meta-analysis. *Frontiers in Plant Science*, 15, 1448070. <https://doi.org/10.3389/fpls.2024.1448070>
- Alrawi, M. S., Aldubaisi, I. A., & Almehemdi, A. F. (2023). Palynological Study of Mimosoideae (Fabaceae) from Baghdad (Iraq). *Phytotaxa*, 622(3), 191-203. <https://doi.org/10.11646/phytotaxa.622.3.2>
- Alyas, T., Shaheen, S., Hussain, F., Harun, N., Hussain, K., Sajjad, S., Ahmed, M., & Khan, F. (2021). Scanning Electron Microscopy-based palynological characterization of selected Euphorbiaceae taxa colonized in Pakistan. *Microscopy Research and Technique*, 84(5), 850-859. <https://doi.org/10.1002/jemt.23644>
- Anandhabhairavi, N., Ambethgar, V., & Philip Sridhar, R. (2020). Foraging behavior of *Apis cerana indica* Fab.(Apidae Hymenoptera) on Cucumber. *Journal of Entomology and Zoology Studies*, 8(6), 189-192.
- Anjum, N., Khan, S., Verma, S., Gaira, K. S., Rawat, B., Chettri, N., & Hanief, M. (2025). Plant-pollinator interactions along the altitudinal gradient in *Berberis lycium royle*: An endangered medicinal plant of the Himalayan region. *PloS One*, 20(5), e0310572. <https://doi.org/10.1371/journal.pone.0310572>
- Arceo-Gómez, G. (2021). Spatial variation in the intensity of interactions via heterospecific pollen transfer may contribute to local and global patterns of plant diversity. *Annals of Botany*, 128(4), 383-394. <https://doi.org/10.1093/aob/mcab082>
- Ariano, R., Mistrello, G., Mincigrucci, G., Bricchi, E., Iannotti, O., Frenguelli, G., Passalacqua, G., & Panzani, R. C. (2006). In vitro and in vivo biological activities of old and fresh Cupressus. *Journal of Investigational Allergology and Clinical Immunology*, 16(3), 177-182.

- Armstrong, J. E., & Drummond III, B. A. (1986). Floral biology of *Myristica fragrans* Houtt.(Myristicaceae), the nutmeg of commerce. *Biotropica*, 32-38. <https://doi.org/10.2307/2388359>
- Arroyo, M. T. K., Armesto, J. J., & Villagran, C. (1981). Plant phenological patterns in the high Andean Cordillera of central Chile. *The Journal of Ecology*, 69(1), 205-223. <https://doi.org/10.2307/2259826>
- Arroyo, M. T., Dudley, L. S., Jespersen, G., Pacheco, D. A., & Cavieres, L. A. (2013). Temperature-driven flower longevity in a high-alpine species of *Oxalis* influences reproductive assurance. *New Phytologist*, 200(4), 1260-1268. <https://doi.org/10.1111/nph.12443>
- Arroyo, M. T., Tamburrino, Í., Pliscoff, P., Robles, V., Colldecarrera, M., & Guerrero, P. C. (2021). Flowering phenology adjustment and flower longevity in a South American alpine species. *Plants*, 10(3), 461. <https://doi.org/10.3390/plants10030461>
- Artamendi, M., Martin, P. A., Bartomeus, I., & Magrach, A. (2025). Loss of pollinator diversity consistently reduces reproductive success for wild and cultivated plants. *Nature Ecology & Evolution*, 9(2), 296-313. <https://doi.org/10.1038/s41559-024-02595-2>
- Aswani, K., & Sabu, M. (2017). Pollination biology of *Curcuma aeruginosa* (Zingiberaceae): an important medicinal plant. *The International Journal of Plant Reproductive Biology*, 9(1), 32-36.
- Aswathi, P., Aswani, K., & Sabu, M. (2018). Reproductive biology of Malabar tamarind (*Garcinia gummi-gutta* (L.) rob): an endemic, medicinal and spice plant from Western Ghats. *The International Journal of Plant Reproductive Biology*, 10(1), 65-68. <https://doi.org/10.14787/ijprb.201810.1.65-68>
- Augspurger, C. K. (1983). Seed dispersal of the tropical tree, *Platypodium elegans*, and the escape of its seedlings from fungal pathogens. *The Journal of Ecology*, 759-771. <https://doi.org/10.2307/2259591>
- Austin, M. W., Smith, A. B., Olsen, K. M., Hoch, P. C., Krakos, K. N., Schmocker, S. P., & Miller-Struttmann, N. E. (2024). Climate change increases flowering duration, driving phenological reassembly and elevated co-flowering richness. *New Phytologist*, 243(6), 2486-2500. <https://doi.org/10.1111/nph.19994>
- Ayyanar, M., Silambarasan, R., Sureshkumar, J., & Gurav, S. S. (2021). Reproductive biology of East Indian satinwood (*Chloroxylon swietenia* DC., Rutaceae: Sapindales), a threatened timber-yielding tree. *Journal of Asia-Pacific Biodiversity*, 14(2), 209-220. <https://doi.org/10.1016/j.japb.2021.01.003>
- Babynin, E., Dubrovnyaya, S., & Kayumov, A. (2023). The effect of ecological factors on genetic polymorphism in natural populations of *Fragaria vesca*. *Theoretical and Applied Ecology*. <https://doi.org/10.25750/1995-4301-2023-3-171-178>
- Baker, H. G. (1967). The evolution of weedy taxa in the *Eupatorium microstemon* species aggregate. *Taxon*, 16(4), 293-300. <https://doi.org/10.2307/1216377>

- Baker, H. G. (1975). Sugar concentrations in nectars from hummingbird flowers. *Biotropica*, 7(1), 37-41. <https://doi.org/10.2307/2989798>
- Baker, H. G., & Baker, I. (1982). Chemical constituents of nectar in relation to pollination mechanisms and phylogeny. In: *Biochemical Aspects of Evolutionary Biology*. Nitecki, H.M. (Ed.), University of Chicago Press, Chicago, pp. 137–171.
- Baker, H. G., & Baker, I. (1983). Floral nectar sugar constituents in relation to pollinator type. In: *Handbook of experimental pollination biology*. Jones, C.E. and Little, R.J (eds). Van Nostrand Reinhold Jones, New York. 117-141.
- Balducci, M. G., Van der Niet, T., & Johnson, S. D. (2020). Diel scent and nectar rhythms of an African orchid in relation to bimodal activity patterns of hawkmoth pollinators. *Annals of Botany*, 126(7), 1155-1164. <https://doi.org/10.1093/aob/mcaa132>
- 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. <https://doi.org/10.1371/journal.pone.0260576>
- Barbosa, J. F., Paulino, J. V., Rodrigues, D., & Sakuragui, C. M. (2018). Floral structure of *Philodendron propinquum* (Araceae) and a comparative study of the *Philodendron* subgenera. *Flora*, 240, 1-6. <https://doi.org/10.1016/j.flora.2017.12.007>
- Barbot, E., Dufaÿ, M., Godé, C., & De Cauwer, I. (2025). Investigating the effects of diurnal and nocturnal pollinators on male and female reproductive success and on floral trait selection in *Silene dioica*. *Peer Community Journal*, 5. <https://doi.org/10.24072/pcjournal.508>
- Barman, C., Singh, V. K., & Tandon, R. (2018). Reproductive biology of *Salvadora oleoides* Decne.(Salvadoraceae). *International Journal of Plant Reproductive Biology*, 10(1), 69-76. <https://doi.org/10.14787/ijprb.2018.10.1.69-76>
- Barreda-Castillo, J. M., Pansarin, E. R., Monribot-Villanueva, J. L., Guerrero-Analco, J. A., & Menchaca-García, R. A. (2024). Allogamy, metaxenia and hybrids in orchids, what do we know about it?. *Botanical Sciences*, 102(3), 646-670. <https://doi.org/10.17129/botsoci.3470>
- Barrett, A., & Brown, L. (2021). Effects of rainfall, temperature and photoperiod on the phenology of ephemeral resources for selected bushveld woody plant species in southern Africa. *Plos One*, 16(5), e0251421. <https://doi.org/10.1371/journal.pone.0251421>
- Barrett, S. C. (2010). Darwin's legacy: the forms, function and sexual diversity of flowers. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1539), 351-368. <https://doi.org/10.1098/rstb.2009.0212>
- Barrett, S. C., & Harder, L. D. (2017). The ecology of mating and its evolutionary consequences in seed plants. *Annual Review of Ecology, Evolution, and*

- Systematics*, 48(1), 135-157. <https://doi.org/10.1146/annurev-ecolsys-110316-023021>
- Barrow, J. R. (1981). A New Concept in Assessing Cotton Pollen Germinability 1. *Crop Science*, 21(3), 441-443. <https://doi.org/10.2135/cropsci1981.0011183X002100030022x>
- Bashir, M. A., Bertamini, M., Gottardini, E., Grando, M. S., & Faralli, M. (2024). Olive (*Olea europaea* L.) reproductive biology: implications for yield, compatibility conundrum, environmental constraints. *Journal of Experimental Botany*, 75(14), 4300-4313.. <https://doi.org/10.1093/jxb/erae190>
- Baskaran, M., & Thiyagesan, K. (2013). Biometric studies of the Indian honey bee *Apis cerana indica* (Fabr.) in the Nagapattinam District, Tamil Nadu, Southern India. *Journal of Apicultural Research*, 52(2), 15-23. <https://doi.org/10.3896/IBRA.1.52.2.04>
- Bawa, K. S. (1990). Plant-pollinator interactions in tropical rain forests. *Annual review of Ecology and Systematics*, 399-422. <https://www.jstor.org/stable/2097031>
- Bell, G. (1985). On the function of flowers. *Proceedings of the Royal society of London. Series B. Biological sciences*, 224(1235), 223-265. <https://doi.org/10.1098/rspb.1985.0031>
- Beltrán, R., Valls, A., Cebrián, N., Zornoza, C., Breijo, F. G., Armiñana, J. R., Garmendia, A., & Merle, H. (2019). Effect of temperature on pollen germination for several Rosaceae species: influence of freezing conservation time on germination patterns. *PeerJ*, 7, e8195. <https://doi.org/10.7717/peerj.8195>
- Bergamo, P. J., Streher, N. S., Zambon, V., Wolowski, M., & Sazima, M. (2021). Pollination generalization and reproductive assurance by selfing in a tropical montane ecosystem. *Science of Nature*, 108, 1-21. <https://doi.org/10.1007/s00114-021-01764-8>
- Bernhardt, C. E., Mitchell, R. J., & Michaels, H. J. (2008). Effects of population size and density on pollinator visitation, pollinator behavior, and pollen tube abundance in *Lupinus perennis*. *International Journal of Plant Sciences*, 169(7), 944-953.
- Beyhan, N., & Serdar, U. (2008). Assessment of pollen viability and germinability in some European chestnut genotypes (*Castanea sativa* L.). *Horticultural Science*, 35(4), 171.
- Bhagawati, S., Rahman, A., & Deka, M. K. (2016). Diversity of insect foragers with reference to foraging behaviour of Asian honey bee, *Apis cerana* F. on sesamum, *Sesamum indicum* L. *Journal of Entomological Research*, 40(3), 213-216. <https://doi.org/10.5958/0974-4576.2016.00039.6>
- Bhat, D. M. (1992). Phenology of tree species of tropical moist forest of Uttara Kannada district, Karnataka, India. *Journal of Biosciences*, 17, 325-352. <https://doi.org/10.1007/BF02703158>

- Bhattacharya, A. (2004). Flower visitors and fruit set of *Anacardium occidentale*. *Annales Botanici Fennici*, 41, 385–392.
- Bhattacharya, A., & Mandal, S. (2004). Pollination, pollen germination and stigma receptivity in *Moringa oleifera* Lamk. *Grana*, 43(1), 48-56. <https://doi.org/10.1080/00173134.2004.11877463>
- 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. [https://doi.org/10.1890/0012-9658\(1998\)079\[0534:VIFPAI\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1998)079[0534:VIFPAI]2.0.CO;2)
- Bitá, C. E., & Gerats, T. (2013). Plant tolerance to high temperature in a changing environment: scientific fundamentals and production of heat stress-tolerant crops. *Frontiers in Plant Science*, 4, 273. <https://doi.org/10.3389/fpls.2013.00273>
- Bleilholder, H., Kirfel, H., Langeluddeke, P., & Stauss, R. (1991). Codificação unificada dos estádios fenológicos de culturas e ervas daninhas. *Pesquisa agropecuária brasileira*, 26, 1423-1429.
- Blionis, G. J., Halley, J. M., & Vokou, D. (2001). Flowering phenology of *Campanula* on Mt Olynipos, Greece. *Ecography*, 24(6), 696-706. <https://doi.org/10.1111/j.1600-0587.2001.tb00531.x>
- Bodó, A., Farkas, Á., Nagy, D. U., Rudolf, K., Hoffmann, R., Kocsis, M., & Morschhauser, T. (2021). Soil humus, iron, sulphate and magnesium content affect nectar traits of wild garlic (*Allium ursinum* L.). *Plants*, 10(3), 597. <https://doi.org/10.3390/plants10030597>
- Bogdziewicz, M., Pesendorfer, M., Crone, E. E., Pérez-Izquierdo, C., & Bonal, R. (2020). Flowering synchrony drives reproductive success in a wind-pollinated tree. *Ecology Letters*, 23(12), 1820-1826. <https://doi.org/10.1111/ele.13609>
- Boillat, S., Mathez-Stiefel, S. L., & Rist, S. (2013). Linking local knowledge, conservation practices and ecosystem diversity: comparing two communities in the Tunari National Park (Bolivia). *Ethnobiology and Conservation*, 2. <https://doi.org/10.15451/ec2013-8-2.8-1-28>
- 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. <https://doi.org/10.1111/j.1466-822X.2004.00111.x>
- Boulter, S. L., Kitching, R. L., Gross, C. L., Goodall, K. L., & Howle, B. G. (2009). Floral morphology, phenology and pollination in the wet tropics. *Living in a dynamic tropical forest landscape*, 224.
- Brajendra, A. V., & Sarma, M. (2016). Soil acidity characterization under different land use systems of Mizoram. *An Asian Journal of Soil Science*, 11(1), 110-114. <https://doi.org/10.15740/HAS/AJSS/11.1/110-114>

- 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. <https://doi.org/10.1002/j.1537-2197.1963.tb06564.x>
- Brown, J., York, A., Christie, F., & McCarthy, M. (2017). Effects of fire on pollinators and pollination. *Journal of Applied Ecology*, 54(1), 313-322. <https://doi.org/10.1111/1365-2664.12670>
- Bruckman, D., & Campbell, D. R. (2014). Floral neighborhood influences pollinator assemblages and effective pollination in a native plant. *Oecologia*, 176, 465-476. <https://doi.org/10.1007/s00442-014-3023-6>
- Buchner, L., Eisen, A. K., Šikoparija, B., & Jochner-Oette, S. (2022). Pollen viability of *Fraxinus excelsior* in storage experiments and investigations on the potential effect of long-range transport. *Forests*, 13(4), 600. <https://doi.org/10.3390/f13040600>
- Buddendorf, S. W., Visser, M. E., & Spoelstra, K. (2025). Temperature amplifies the effect of anthropogenic light on foraging common pipistrelle bats. *Biology Letters*, 21(6), 20250049. <https://doi.org/10.1098/rsbl.2025.0049>
- Burkle, L. A., & Irwin, R. E. (2009). The effects of nutrient addition on floral characters and pollination in two subalpine plants, *Ipomopsis aggregata* and *Linum lewisii*. *Plant Ecology*, 203, 83-98. <https://doi.org/10.1007/s11258-008-9512-0>
- Burns, K. L., Fitzpatrick, Ú., & Stanley, D. A. (2021). Public perceptions of Ireland's pollinators: a case for more inclusive pollinator conservation initiatives. *Journal for Nature Conservation*, 61, 125999. <https://doi.org/10.1016/j.jnc.2021.125999>
- Byers, D. L. (2017). Studying plant–pollinator interactions in a changing climate: a review of approaches. *Applications in Plant Sciences*, 5(6), 1700012. <https://doi.org/10.3732/apps.1700012>
- Caccavari, M. A. (2002). Pollen morphology and structure of Tropical and Subtropical American genera of the Piptadenia-group (Leguminosae: Mimosoideae). *Grana*, 41(3), 130-141. <https://doi.org/10.1080/001731302321042597>
- Caceres, M. E., Pupilli, F., Sarri, V., Mencuccini, M., & Ceccarelli, M. (2016). Floral biology in *Olea europaea* subsp. *cuspidata*: a comparative structural and functional characterization. *Flora-Morphology, Distribution, Functional Ecology of Plants*, 222, 27-36. <https://doi.org/10.1016/j.flora.2016.03.006>
- Cannon, C. H., Borchetta, C., Anderson, D. L., Arellano, G., Barker, M., Charron, G., LaMontagne, J. M., Richards, J. H., Abercrombie, E., Banin, L. F., Casapia, X. T., Chen, X., Degtjarenko, P., Dell, J.E., Durden, D., Andino, J. E. G., Hernández-Gutiérrez, R., Hirons, A. D., Kua, C., Vigne, H. L., Laponce, M., Lim, J. Y., Lowman, M., Marshall, A. J., Michaletz, S. T., Normark, B. B., Penneys, D. S., Schneider, G. F., Strijk, J. S., Tiamiyu, B. B., Trammell, T. L. E., Vargas-Rodriguez, Y. L., Weintraub-Leff, S. R., Desbiens, A. L., & Spenko, M. (2021). Extending our scientific reach in arboreal ecosystems for research

- and management. *Frontiers in Forests and Global Change*, 4, 712165. <https://doi.org/10.3389/ffgc.2021.712165>
- Carvalho, L. G., Bartomeus, I., Rollin, O., Timóteo, S., & Tinoco, C. F. (2021). The role of soils on pollination and seed dispersal. *Philosophical Transactions of the Royal Society B*, 376(1834), 20200171. <https://doi.org/10.1098/rstb.2020.0171>
- Carvalho, A. M., & Frazão-Moreira, A. (2011). Importance of local knowledge in plant resources management and conservation in two protected areas from Trás-os-Montes, Portugal. *Journal of Ethnobiology and Ethnomedicine*, 7, 1-13. <https://doi.org/10.1186/1746-4269-7-36>
- Cebrián-Piqueras, M. A., Filyushkina, A., Johnson, D. N., Lo, V. B., López-Rodríguez, M. D., March, H., Oteros-Rozas, E., Peppler-Lisbach, C., Quintas-Soriano, C., Raymond, C. M., Ruiz-Mallén, I., van Riper, C. J., Zinngrebe, Y., & Plieninger, T. (2020). Scientific and local ecological knowledge, shaping perceptions towards protected areas and related ecosystem services. *Landscape Ecology*, 35(11), 2549-2567. <https://doi.org/10.1007/s10980-020-01107-4>
- Cerezini, M. T., Rattis, L., Furini, P. R., & Pereira, R. A. (2024). Contrasting Phenological Patterns and Reproductive Strategies in Closely Related Monoecious Fig Tree Species. *Plants*, 13(14), 1889. <https://doi.org/10.3390/plants13141889>
- Cha, Y. P., Irwin, R. E., Wu, Y., Ma, Y. M., Shuang, S., & Zhang, Z. Q. (2025). Soil moisture influences nectar robbing and plant fitness in a primrose species. *Journal of Ecology*. <https://doi.org/10.1111/1365-2745.70067>
- Chabert, S., Sénéchal, C., Fougereux, A., Pousse, J., Richard, F., Nozières, E., Geist, O., Guillemard, V., , Leylaverne, S., Malard, C., Benoist, A., Carré, G., Caumes, E., Cenier, C., Treil, A., Danflous, S., & Vaissière, B. E. (2020). Effect of environmental conditions and genotype on nectar secretion in sunflower (*Helianthus annuus* L.). *OCL*, 27, 51. <https://doi.org/10.1051/ocl/2020040>
- Chandarak, N., Somjinda, P., Phoncharoen, P., Banterng, P., Taratima, W., Theerakulpisut, P., & Dongsansuk, A. (2023). Booting heat stress alters leaf photosynthesis, growth rate, phenology and yield in rice. *Plant Stress*, 10, 100226. <https://doi.org/10.1016/j.stress.2023.100226>
- Chapman, K. E., Cozma, N. E., Hodgkinson, A. B., English, R., Gaston, K. J., & de Ibarra, N. H. (2022). Bumble bees exploit known sources but return with partial pollen loads when foraging under low evening light. *Animal Behaviour*, 194, 127-137. <https://doi.org/10.1016/j.anbehav.2022.09.010>
- Charlesworth, D. (2006). Evolution of plant breeding systems. *Current Biology*, 16(17), R726-R735. <https://doi.org/10.1016/j.cub.2006.07.068>
- Chatkin, J., Correa, L., & Santos, U. (2022). External environmental pollution as a risk factor for asthma. *Clinical Reviews in Allergy and Immunology*, 62(1), 72-89. <https://doi.org/10.1007/s12016-020-08830-5>

- Chauhan, S. (2019). Floral and pollination biology of *Saraca asoca* (Roxb.) De Wilde (Caesalpinioideae). *International Journal of Plant Reproductive Biology*, 1 1(1), 31-37.
- Chauhan, S. C. S. (2015). Phenological studies in *Litchi chinensis* Sonn.(Sapindaceae). *International Journal of Plant Reproductive Biology*, 7(1), 88-90.
- Chaves, S. R., dos Santos, R. R., & da Silva, A. L. G. (2020). Reproductive biology of *Parkia platycephala* Benth (Leguminosae, Caesalpinioideae, clado mimosoide). *Brazilian Journal of Development*, 6(10), 79442-79458. <https://doi.org/10.34117/bjdv6n10-393>
- Chen, L., Cai, Y., Quan, Q., & Li, Y. (2025). Interplay of Temporal Variation in Nectar Parameters and Pollinator-Mediated Adaptations in *Epimedium wushanense*. *Phyton* (0031-9457), 94(5). <https://doi.org/10.32604/phyton.2025.064112>
- Chen, X., Wang, J., Liu, W., & Zhang, Y. (2024). The relative effects of climatic drivers and phenotypic integration on phenotypic plasticity of a globally invasive plant. *Frontiers in Plant Science*, 15, 1473456. <https://doi.org/10.3389/fpls.2024.1473456>
- Chen, Y., Chen, G., Yang, J., & Sun, W. (2016). Reproductive biology of *Magnolia sinica* (Magnoliaceae), a threatened species with extremely small populations in Yunnan, China. *Plant Diversity*, 38(5), 253-258. <https://doi.org/10.1016/j.pld.2016.09.003>
- Cheptou, P. O. (2019). Does the evolution of self-fertilization rescue populations or increase the risk of extinction?. *Annals of Botany*, 123(2), 337-345. <https://doi.org/10.1093/aob/mcy144>
- Cheung, A. Y., Duan, Q. H., Costa, S. S., De Graaf, B. H., Di Stilio, V. S., Feijo, J., & Wu, H. M. (2008). The dynamic pollen tube cytoskeleton: live cell studies using actin-binding and microtubule-binding reporter proteins. *Molecular Plant*, 1(4), 686-702. <https://doi.org/10.1093/mp/ssn026>
- Choudhury, B. U., Nengzouzam, G., & Islam, A. (2022). Runoff and soil erosion in the integrated farming systems based on micro-watersheds under projected climate change scenarios and adaptation strategies in the eastern Himalayan mountain ecosystem (India). *Journal of Environmental Management*, 309, 114667. <https://doi.org/10.1016/j.jenvman.2022.114667>
- Choudhury, S., Mondal, S., & Mandal, S. (2017). Floral phenology, flower-visitor interaction and pollination of *Abrus precatorius* L. *International Journal of Plant Reproductive Biology*, 9(1), 53-58.
- Christiansen, N. A. (2023). Restoring the 3D Structure of Tropical Ecosystems—how Important is Tree Diversity? (Doctoral dissertation, University of Bristol).
- Christmas, M. J., Breed, M. F., & Lowe, A. J. (2016). Constraints to and conservation implications for climate change adaptation in plants. *Conservation Genetics*, 17, 305-320. <https://doi.org/10.1007/s10592-015-0782-5>

- Cleland, E. E., & Wolkovich, E. M. (2024). Effects of Phenology on Plant Community Assembly and Structure. *Annual Review of Ecology, Evolution, and Systematics*, 55(1), 471-492. <https://doi.org/10.1146/annurev-ecolsys-102722-011653>
- Coates, J., Evans, M., Scheele, B., Encinas-Viso, F., Florez Fernandez, J., Lumbers, J., & Cunningham, S. A. (2024). Influence of climate, weather and floral associations on pollinator community composition across an elevational gradient. *Oikos*, 2024(12), e10688. <https://doi.org/10.1111/oik.10688>
- Coelho, A. P., Morais, K. P., Laughinghouse IV, D., Giacomini, S. J., & Tedesco, S. B. (2012). Pollen grain viability in accessions of *Crotalaria juncea* L.(Fabaceae). *Agrociencia*, 46(5), 481-487.
- Comizzoli, P., & Holt, W. (2019). Breakthroughs and new horizons in reproductive biology of rare and endangered animal species. *Biology of Reproduction*, 101, 514 - 525. <https://doi.org/10.1093/biolre/ioz031>
- Coomes, D. A., & Grubb, P. J. (2000). Impacts of root competition in forests and woodlands: a theoretical framework and review of experiments. *Ecological Monographs*, 70(2), 171-207. [https://doi.org/10.1890/0012-9615\(2000\)070\[0171:IORCIF\]2.0.CO;2](https://doi.org/10.1890/0012-9615(2000)070[0171:IORCIF]2.0.CO;2)
- Corbet, S. A. (2003). Nectar sugar content: estimating standing crop and secretion rate in the field. *Apidologie*, 34(1), 1-10. <https://doi.org/10.1051/apido:2002049>
- Cordero, S., Galvez, F., & Fonturbel, F. E. (2023). Ecological impacts of exotic species on native seed dispersal systems: a systematic review. *Plants*, 12(2), 261. <https://doi.org/10.3390/plants12020261>
- Corlett, R. T. (2004). Flower visitors and pollination in the Oriental (Indomalayan) Region. *Biological Reviews*, 79(3), 497-532. <https://doi.org/10.1017/S1464793103006341>
- Crall, J. D., Brokaw, J., Gagliardi, S. F., Mendenhall, C. D., Pierce, N. E., & Combes, S. A. (2020). Wind drives temporal variation in pollinator visitation in a fragmented tropical forest. *Biology Letters*, 16(4), 20200103. <https://doi.org/10.1098/rsbl.2020.0103>
- Creux, N. M., Brown, R. I., Garner, A. G., Saeed, S., Scher, C. L., Holalu, S. V., Yang, D., Maloof, J.N., Blackman, B. K., & Harmer, S. L. (2021). Flower orientation influences floral temperature, pollinator visits and plant fitness. *New Phytologist*, 232(2), 868-879. <https://doi.org/10.1111/nph.17627>
- Crispim, J. G., Rêgo, E. R., Rêgo, M. M., Nascimento, N. F. F., & Barroso, P. A. (2017). Stigma receptivity and anther dehiscence in ornamental pepper. *Horticultura Brasileira*, 35(4), 609-612. <https://doi.org/10.1590/S0102-053620170421>
- Cruden, R. W. (1973). Reproductive biology of weedy and cultivated *Mirabilis* (Nyctaginaceae). *American Journal of Botany*, 60(8), 802-809. <https://doi.org/10.1002/j.1537-2197.1973.tb07592.x>

- Cruden, R. W. (1977). Pollen-ovule ratios: a conservative indicator of breeding systems in flowering plants. *Evolution*, 32-46. <https://doi.org/10.1111/j.1558-5646.1977.tb00979.x>
- Daele, F. V., Honnay, O., Janssens, S., & De Kort, H. (2024). Habitat fragmentation affects climate adaptation in a forest herb. *Journal of Ecology*, 112(2), 246-264. <https://doi.org/10.1111/1365-2745.14225>
- Daele, F. V. (2024). Plant conservation in a changing world: modelling range dynamics, climate adaptation, and effects of habitat fragmentation.
- Dafni, A. (1992). *Pollination Ecology, a Practical Approach*. Oxford University Press, Oxford.
- Dafni, A., & Maués, M. M. (1998). A rapid and simple procedure to determine stigma receptivity. *Sexual Plant Reproduction*, 11 (3), 177-180. <https://doi.org/10.1007/s004970050138>
- Dafni, A., Kevan, P. G., & Husband, B. C. (2005). *Practical pollination biology*. Enviroquest Ltd., Cambridge, Ontario, Canada. 590p.
- Datta, A., Banerjee, S., Naniwadekar, R., Thapa, K., Rathore, A., Thapa, K., Brah, T., Nabum, T., Shukla, U., Sidhu, S., & Borawake, N. (2024). Patterns of leaf, flower and fruit phenology and environmental relationships in a seasonal tropical forest in the Indian Eastern Himalaya. *bioRxiv*, 2024-09. <https://doi.org/10.1101/2024.09.29.615687>
- de Andrade, A. P., da Silva, D. S., de Lucena Alcantara Bruno, R., da Silva, D. L. S., de Andrade Melo Junior, J. L., Magalhaes, A. L. R., de Andrade Melo, L. D. F., & de Medeiros, A. N. (2020). Temporal rainfall variability as inductor of the phenology of Brazilian semiarid species. *Australian Journal of Crop Science*, 14(2), 299-307.
- de Carvalho, A. L. G., Somner, G. V., & Allen, J. (2015). Is the phenology of all restinga species the same? A taxonomically-focused study of Sapindaceae in a highly threatened coastal environment. *Flora-Morphology, Distribution, Functional Ecology of Plants*, 215, 92-101. <https://doi.org/10.1016/j.flora.2015.06.005>
- de Sousa, F. G., dos Santos, J. S., Martello, F., Diniz, M. F., Bergamini, L. L., Ribeiro, M. C., Collevatti, R. G., & Silva, D. P. (2022). Natural habitat cover and fragmentation per se influence orchid-bee species richness in agricultural landscapes in the Brazilian Cerrado. *Apidologie*, 53(2), 20. <https://doi.org/10.1007/s13592-022-00925-6>
- De Storme, N., & Geelen, D. (2014). The impact of environmental stress on male reproductive development in plants: biological processes and molecular mechanisms. *Plant, Cell and Environment*, 37(1), 1-18. <https://doi.org/10.1111/pce.12142>

- Descamps, C., Jambrek, A., Quinet, M., & Jacquemart, A. L. (2021). Warm temperatures reduce flower attractiveness and bumblebee foraging. *Insects*, 12(6), 493. <https://doi.org/10.3390/insects12060493>
- Deyto, R. C., & Cervancia, C. R. (2022). Floral biology and pollination of red hot F1 hybrid hot pepper (*Capsicum frutescens* x *C. annuum*) in The Philippines. *Philippine Agricultural Scientist*, 105(2), 133-146.
- Dobson, H. E. M. (2006). Relationship between floral fragrance composition and type of pollinator. In: *Biology of Floral Scent*. Dudareva, N. and Pichersky, E. (eds.), Taylor & Francis, New York, pp. 147-198.
- Dolui, A. K., & Mondal, A. (2007). Influence of different forms of iron and aluminum on the nature of soil acidity of some Inceptisols, alfisols, and Ultisols. *Communications in Soil Science and Plant Analysis*, 38(1-2), 119-131. <https://doi.org/10.1080/00103620601093827>
- Dorji, T., Hopping, K. A., Meng, F., Wang, S., Jiang, L., & Klein, J. A. (2020). Impacts of climate change on flowering phenology and production in alpine plants: The importance of end of flowering. *Agriculture, Ecosystems & Environment*, 291, 106795. <https://doi.org/10.1016/j.agee.2019.106795>
- Dorji, T., Totland, Ø., Moe, S., Hopping, K., Pan, J., & Klein, J. (2013). Plant functional traits mediate reproductive phenology and success in response to experimental warming and snow addition in Tibet. *Global Change Biology*, 19. <https://doi.org/10.1111/gcb.12059>
- Duan, Y. W., Ren, M. X., Gong, Y. B., Tian, B., & Caujapé-Castells, J. (2024). Molecular ecology of plant sexual reproduction. *Frontiers in Plant Science*, 15, 1362777. <https://doi.org/10.3389/fpls.2024.1362777>
- Duarte, A. F. T., Ribeiro, P. G., Moreira, A. L. D. C., de Queiroz, L. P., & de Assis Ribeiro dos Santos, F. (2021). Pollen morphology of Senegalia Raf. species and related genera (Leguminosae: Caesalpinioideae: mimosoid clade). *Palynology*, 45(4), 627-639. <https://doi.org/10.1080/01916122.2021.1890256>
- Dzul-Cauich, H. F., & Munguía-Rosas, M. A. (2025). Effects of Urbanization on Flowering Phenology, Pollination, and Reproductive Success in the Chiropterophilous Tropical Tree *Ceiba pentandra*. *Plants*, 14(11), 1575. <https://doi.org/10.3390/plants14111575>
- Eckhart, V. M. (1991). The effects of floral display on pollinator visitation vary among populations of *Phacelia linearis* (Hydrophyllaceae). *Evolutionary Ecology*, 5, 370-384. <https://doi.org/10.1007/BF02214154>
- Edlund, A. F., Swanson, R., & Preuss, D. (2004). Pollen and stigma structure and function: the role of diversity in pollination. *Plant Cell*, 16(suppl_1), S84-S97. <https://doi.org/10.1105/tpc.015800>
- Edwards, C. B., Schultz, C. B., Campbell, S. P., Fallon, C., Henry, E. H., King, K. C., Linders, M., Longcore, T., Marschalek, D. A., Sinclair, D., Swengel, A., Swengel, S., Taron, D. J., Wepprich, T., & Crone, E. E. (2024). Phenological

- constancy and management interventions predict population trends in at-risk butterflies in the United States. *Journal of Applied Ecology*, 61(10), 2455-2469. <https://doi.org/10.1111/1365-2664.14735>
- Eichenwald, A. J., Fefferman, N. H., & Reed, J. M. (2024). Potential extinction cascades in a desert ecosystem: Linking food web interactions to community viability. *Ecology and Evolution*, 14(2), e10930. <https://doi.org/10.1002/ece3.10930>
- Eilers, E. J., Kleine, S., Eckert, S., Waldherr, S., & Müller, C. (2021). Flower production, headspace volatiles, pollen nutrients, and florivory in *Tanacetum vulgare* chemotypes. *Frontiers in Plant Science*, 11, 611877. <https://doi.org/10.3389/fpls.2020.611877>
- Eisenhauer, N., Schielzeth, H., Barnes, A., Barry, K., Bonn, A., Brose, U., Bruehlheide, H., Buchmann, N., Buscot, F., Ebeling, A., Ferlian, O., Freschet, G., Giling, D., Hättenschwiler, S., Hillebrand, H., Hines, J., Isbell, F., Koller-France, E., König-Ries, B., De Kroon, H., Meyer, S., Milcu, A., Müller, J., Nock, C., Petermann, J., Roscher, C., Scherber, C., Scherer-Lorenzen, M., Schmid, B., Schnitzer, S., Schuldt, A., Tschamntke, T., Türke, M., Van Dam, N., Van Der Plas, F., Vogel, A., Wagg, C., Wardle, D., Weigelt, A., Weisser, W., Wirth, C., & Jochum, M. (2019). A multitrophic perspective on biodiversity-ecosystem functioning research.. *Advances in Ecological Research*, 61, 1-54 . <https://doi.org/10.1016/BS.AECCR.2019.06.001>
- El Ottra, J. H. L., Pirani, J. R., & Pansarin, E. R. (2016). Floral biology and pollination of two sympatric species of Galipeinae (Galipeae, Rutaceae) endemic to the Brazilian Atlantic Forest. *Flora*, 221, 107-116. <https://doi.org/10.1016/j.flora.2015.12.006>
- Elmendorf, S. C., & Hollister, R. D. (2023). Limits on phenological response to high temperature in the Arctic. *Scientific Reports*, 13(1), 208. <https://doi.org/10.1038/s41598-022-26955-9>
- 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 and Evolution*, 22(8), 432-439. <https://doi.org/10.1016/j.tree.2007.05.006>
- Endress, P. K. (1994). Diversity and evolutionary biology of tropical flowers. Cambridge, Cambridge University Press.
- Erickson, E., Junker, R. R., Ali, J. G., McCartney, N., Patch, H. M., & Grozinger, C. M. (2022). Complex floral traits shape pollinator attraction to ornamental plants. *Annals of Botany*, 130(4), 561-577. <https://doi.org/10.1093/aob/mcac082>
- Evans, M. E., Menges, E. S., & Gordon, D. R. (2003). Reproductive biology of three sympatric endangered plants endemic to Florida scrub. *Biological Conservation*, 111(2), 235-246. [https://doi.org/10.1016/S0006-3207\(02\)00293-8](https://doi.org/10.1016/S0006-3207(02)00293-8)

- Fábián, A., Sáfrán, E., Szabó-Eitel, G., Barnabás, B., & Jäger, K. (2019). Stigma functionality and fertility are reduced by heat and drought co-stress in wheat. *Frontiers in Plant Science*, 10, 244. <https://doi.org/10.3389/fpls.2019.00244>
- Farkas, Á., Molnár, R., Morschhauser, T., & Hahn, I. (2012). Variation in nectar volume and sugar concentration of *Allium ursinum* L. ssp. *ucrainicum* in three habitats. *Scientific World Journal*, 2012(1), 138579. <https://doi.org/10.1100/2012/138579>
- Fenster, C. B., & Marten-Rodriguez, S. (2007). Reproductive assurance and the evolution of pollination specialization. *International Journal of Plant Sciences*, 168(2), 215-228.
- Ferreira, B. H. S., Gomes, A. C., Souza, C. S., Fabri, J. R., & Sigrist, M. R. (2018). Pollination and reproductive system of synchronopatric species of Cactaceae (Cactoideae) subject to interspecific flow of pollen: an example of ecological adaptation in the Brazilian Chaco. *Plant Biology*, 20(1), 101-112. <https://doi.org/10.1111/plb.12641>
- Ferreira, P. A., Boscolo, D., Lopes, L. E., Carnevalheiro, L. G., Biesmeijer, J. C., da Rocha, P. L. B., & Viana, B. F. (2020). Forest and connectivity loss simplify tropical pollination networks. *Oecologia*, 192, 577-590. <https://doi.org/10.1007/s00442-019-04579-7>
- Ferrer, M. M., Vásquez-Cruz, M., Verde-Cáceres, M. A., Magaña-Rosado, U. C., & Good, S. V. (2024). The distribution of self-incompatibility systems in angiosperms: the relationship between mating system diversity, life span, growth habit and latitude in a changing global environment. *Annals of Botany*, mcae056. <https://doi.org/10.1093/aob/mcae056>
- Fill, C. T., Allen, C. R., Twidwell, D., & Benson, J. F. (2022). Spatial distribution of bat activity in agricultural fields: implications for ecosystem service estimates. *Ecology and Society*, 27(2). <https://doi.org/10.5751/ES-13170-270211>
- Fisogni, A., Cristofolini, G., Rossi, M., & Galloni, M. (2011). Pollinator directionality as a response to nectar gradient: promoting outcrossing while avoiding geitonogamy. *Plant Biology*, 13(6), 848-856. <https://doi.org/10.1111/j.1438-8677.2011.00453.x>
- Fleming, G. M., Wunderle Jr, J. M., White, J. D., Currie, D., Helmer, E. H., & Ewert, D. N. (2024). Winter dry season reproductive phenology in Bahamian dry forest and implications for conservation. *Biotropica*, 56(1), 170-184. <https://doi.org/10.1111/btp.13294>
- Fornoff, F., Klein, A. M., Hartig, F., Benadi, G., Venjakob, C., Schaefer, H. M., & Ebeling, A. (2017). Functional flower traits and their diversity drive pollinator visitation. *Oikos*, 126(7), 1020-1030. <https://doi.org/10.1111/oik.03869>
- Fournier, L. A. (1974). Un metodo cuantitativo para la medicion de características fenologicas en arboles. *Turrialba*. 24(4), 422-423.

- Fragallah, S. A. D. A., Lin, S., Li, N., Ligate, E. J., & Chen, Y. (2019). Effects of sucrose, boric acid, pH, and incubation time on *in vitro* germination of pollen and tube growth of chinese fir (*Cunninghamia lanceolata* L.). *Forests*, 10(2), 102. <https://doi.org/10.3390/f10020102>
- Freitas, L., & Bolmgren, K. (2008). Synchrony is more than overlap: measuring phenological synchronization considering time length and intensity. *Brazilian Journal of Botany*, 31, 721-724. <https://doi.org/10.1590/S0100-84042008000400017>
- 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. <https://doi.org/10.1093/aob/mcp035>
- Frigerio, M. L. P., Boaro, C. S., Galetto, L., Tunes, P., & Guimarães, E. (2025). Extreme events induced by climate change alter nectar offer to pollinators in cross pollination-dependent crops. *Scientific Reports*, 15(1), 10852. <https://doi.org/10.1038/s41598-025-94565-2>
- Frisk, C. A., Apangu, G. P., Petch, G. M., Creer, S., Hanson, M., Adams-Groom, B., & Skjøth, C. A. (2023). Microscale pollen release and dispersal patterns in flowering grass populations. *Science of the Total Environment*, 880, 163345. <https://doi.org/10.1016/j.scitotenv.2023.163345>
- Fugerey-Scarbel, A., Bouffier, L., Lemarié, S., Sánchez, L., Alia, R., Biselli, C., Buiteveld, J., Carra, A., Cattivelli, L., Dowkiw, A., Fontes, L., Fricano, A., Gion, Grima-Pettenati, J., Helmersson, A., Lario, F., Leal, L., Mutke, S., Nervo, G., Persson, T., Rosso, L., & Haapanen, M. (2024). Prospects for evolution in European tree breeding. *iForest: Biogeosciences and Forestry*, 17(2), 45-58. <https://doi.org/10.3832/for4544-017>
- Gaffney, C. (2016). Foraging Behaviors of *Camponotus Pennsylvanicus* Under Varying Social Density Conditions (Doctoral dissertation, Pennsylvania State University).
- Galetto, L., & Bernardello, G. (2005). Rewards in flowers. Nectar. In: Practical Pollination Biology. Dafni, A., Kevan, P.G. and Husband, B.C. (eds.). Enviroquest, Cambridge, Ontario, pp. 261-313.
- Gamba, D., & Muchhala, N. (2023). Pollinator type strongly impacts gene flow within and among plant populations for six Neotropical species. *Ecology*, 104(1), e3845. <https://doi.org/10.1002/ecy.3845>
- Ganie, A. H., Tali, B. A., Reshi, Z. A., & Nawchoo, I. A. (2021). Inflorescence architecture, floral part movements and pollinator attraction by androecia–contrivance for successful mating in *Eremurus himalaicus* Baker. *Botanica Pacifica*, 10(2), 29-34. <https://doi.org/10.17581/bp.2021.10206>
- Gauzere, J., Klein, E. K., Brendel, O., Davi, H., & Oddou-Muratorio, S. (2020). Microgeographic adaptation and the effect of pollen flow on the adaptive

- potential of a temperate tree species. *New Phytologist*, 227(2), 641-653.
<https://doi.org/10.1111/nph.16537>
- Geethika, K., & Sabu, M. (2017). Pollination biology of *Syzygium caryophyllatum* (L.) Alston (Myrtaceae). *International Journal of Plant Reproductive Biology*, 9(1), 69-72.
- Gérard, M., Vanderplanck, M., Wood, T., & Michez, D. (2020). Global warming and plant–pollinator mismatches. *Emerging Topics in Life Sciences*, 4(1), 77-86.
<https://doi.org/10.1042/ETLS20190139>
- Ghazoul, J. (2005). Pollen and seed dispersal among dispersed plants. *Biological Reviews*, 80(3), 413-443.
- Ghosh, S., Sun, S., Jang, H., & Jung, C. (2024). Amino Acid Dynamics in Bee Feed: Comparative Account of Amino Acid Composition among Pollen, Bee-pollen and Bee Bread. *Journal of Apiculture*, 2, 127-132.
<https://doi.org/10.17519/apiculture.2024.06.39.2.127>
- Giblin, D. E. (2005). Variation in floral longevity between populations of *Campanula rotundifolia* (Campanulaceae) in response to fitness accrual rate manipulation. *American Journal of Botany*, 92(10), 1714-1722.
<https://doi.org/10.3732/ajb.92.10.1714>
- Gibson, J. P. (2001). Ecological and genetic comparison between ray and disc achene pools of the heteromorphic species *Prionopsis ciliata* (Asteraceae). *International Journal of Plant Sciences*, 162(1), 137-145.
<https://doi.org/10.1086/317910>
- Gomasta, J., Sarker, B. C., Alam, A., Kayesh, E., Islam, M., Khan, H. I., & Rahman, M. M. (2025). Floral biology and reproductive phenology of golden apple (*Spondias dulcis* Frost.) in subtropical terrace soil condition. *Discover Plants*, 2(1), 67 <https://doi.org/10.1007/s44372-025-00143-1>
- Gomes, A. S. S., Milet-Pinheiro, P., & Domingos-Melo, A. (2024). Male Emphorini (Hymenoptera: Apidae) bees use flowers of *Ipomoea carnea* (Convolvulaceae) as overnight resting sites. *Biota Neotropica*, 24, e20231604.
<https://doi.org/10.1590/1676-0611-BN-2024-1624>
- Gomez, J. M., Bosch, J., Perfectti, F., Fernández, J. D., Abdelaziz, M., & Camacho, J. P. M. (2008). Spatial variation in selection on corolla shape in a generalist plant is promoted by the preference patterns of its local pollinators. *Proceedings of the Royal Society B: Biological Sciences*, 275(1648), 2241-2249.
<https://doi.org/10.1098/rspb.2008.0512>
- Goodwin, R. M. (1986). Kiwifruit flowers: anther dehiscence and daily collection of pollen by honey bees. *New Zealand Journal of Experimental Agriculture*, 14(4), 449-452. <https://doi.org/10.1080/03015521.1986.10423064>
- Gordo, O., & Sanz, J. J. (2010). Impact of climate change on plant phenology in Mediterranean ecosystems. *Global Change Biology*, 16(3), 1082-1106.
<https://doi.org/10.1111/j.1365-2486.2009.02084.x>

- Göttlinger, T., & Lohaus, G. (2023). Origin and function of amino acids in nectar and nectaries of *Pitcairnia* species with particular emphasis on alanine and glutamine. *Plants*, 13(1), 23. <https://doi.org/10.3390/plants13010023>
- Goudarzi, G., Birgani, Y. T., Assarehzadegan, M. A., Neisi, A., Dastoorpoor, M., Sorooshian, A., & Yazdani, M. (2022). Prediction of airborne pollen concentrations by artificial neural network and their relationship with meteorological parameters and air pollutants. *Journal of Environmental Health Science and Engineering*, 20(1), 251-264. <https://doi.org/10.1007/s40201-021-00773-z>
- Grogan, P., Lalnunmawia, F., & Tripathi, S. K. (2012). Shifting cultivation in steeply sloped regions: a review of management options and research priorities for Mizoram state, Northeast India. *Agroforestry Systems*, 84, 163-177. <https://doi.org/10.1007/s10457-011-9469-1>
- Gumprecht, R. (1977). Seltsame Bestäubungsvorgänge bei Orchideen. *Orchidee*, 28.
- Ha, T. M. (2014). A review of plants' flowering physiology: The control of floral induction by juvenility, temperature and photoperiod in annual and ornamental crops. *Asian Journal of Agriculture and Food Sciences*, 2(3), 186-195.
- Hack, H., Bleiholder, H., Buhr, L., Meier, U., Schnock-Fricke, U., Weber, E., & Witzemberger, A. (1992). A uniform code for phenological growth stages of mono- and dicotyledonous plants. Extended BBCH scale, general. *Nachrichtenblatt Deutscher Pflanzenschutz*, 44, 265-270.
- Hada, V. L. (2024). Pollination biology and breeding behaviour of *Datura innoxia* Mill. *International Journal of Ecology and Environmental Sciences*, 6(1), 37-44.
- Häder, D. P. (2019). Photoecology and environmental photobiology. In CRC Handbook of Organic Photochemistry and Photobiology, Third Edition-Two Volume Set (pp. 1117-1135). CRC Press.
- Haggerty, B. P., & Galloway, L. F. (2011). Response of individual components of reproductive phenology to growing season length in a monocarpic herb. *Journal of Ecology*, 99(1), 242-253. <https://doi.org/10.1111/j.1365-2745.2010.01744.x>
- Hakami, A. R., Khan, K. A., Ghramh, H. A., Ahmad, Z., & Al-Zayd, A. A. A. (2020). Impact of artificial light intensity on nocturnal insect diversity in urban and rural areas of the Asir province, Saudi Arabia. *Plos One*, 15(12), e0242315. <https://doi.org/10.1371/journal.pone.0242315>
- Hamad, H. S., Bleih, E. M., Gewaily, E. E., Alharbi, K., & Rehan, M. (2023). The potential effects of kinetin implementation on hybrid rice seed production under water deficit. *Sustainability*, 15(7), 5623. <https://doi.org/10.3390/su15075623>
- Hamon, L., Youngsteadt, E., Irwin, R., & Sorenson, C. (2024). As prey and pollinators, insects increase reproduction and allow for outcrossing in the carnivorous plant *Dionaea muscipula*. *American Journal of Botany*, e16279. <https://doi.org/10.1002/ajb2.16279>

- Han, H., Chen, Y., Yang, Z., Zhang, X., Ma, Y., & Gan, X. (2025). The reduction in genetic quality of seeds resulting from self-pollination acts as a pivotal factor limiting the regeneration of the endangered plant *Tetracentron sinense* Oliv. *Global Ecology and Conservation*, e03627. <https://doi.org/10.1016/j.gecco.2025.e03627>
- Hanberry, B. B. (2025). Potential expanded pollinator distributions in North America under future climate. *Ecological Solutions and Evidence*, 6(2), e70025. <https://doi.org/10.1002/2688-8319.70025>
- Haq, M. A., Sumangala, K., & Ramani, N. (2010, October). Mites associated with concealed and open nests of *Apis cerana indica* in Kerala, South India. In *Trends in Acarology: Proceedings of the 12th International Congress* (pp. 371-372). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-90-481-9837-5_60
- Harder, L. D., & Barrett, S. C. (1996). Pollen dispersal and mating patterns in animal pollinated plants. In: *Floral biology*. Springer, Boston, MA. pp. 140-190.
- Harder, L. D., & Johnson, S. D. (2008). Function and evolution of aggregated pollen in angiosperms. *International Journal of Plant Sciences*, 169(1), 59-78. <https://doi.org/10.1086/523364>
- Harder, L. D., & Johnson, S. D. (2023). Beyond pollen: ovule ratios: evolutionary consequences of pollinator dependence and pollination efficiency for pollen and ovule production in angiosperms. *American Journal of Botany*, 110(6), e16177. <https://doi.org/10.1002/ajb2.16177>
- Hasegawa, T. M., Itagaki, T., & Sakai, S. (2023). Intraspecific variation in morphology of spiny pollen grains along an altitudinal gradient in an insect-pollinated shrub. *Plant Biology*, 25(2), 287-295. <https://doi.org/10.1111/plb.13493>
- Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, 10(Part A), 4-10. <https://doi.org/10.1016/j.wace.2015.08.001>
- Hedhly, A. (2011). Sensitivity of flowering plant gametophytes to temperature fluctuations. *Environmental and Experimental Botany*, 74, 9-16. <https://doi.org/10.1016/j.envexpbot.2011.03.016>
- Heil, M., Fiala, B., Baumann, B., & Linsenmair, K. E. (2000). Temporal, spatial and biotic variations in extrafloral nectar secretion by *Macaranga tanarius*. *Functional Ecology*, 749-757. <https://doi.org/10.1046/j.1365-2435.2000.00480.x>
- Heinrich, B. (1975). Bee flowers: a hypothesis on flower variety and blooming times. *Evolution*, 325-334. <https://doi.org/10.2307/2407220>
- Henderson, A. (1986). A review of pollination studies in the Palmae. *Botanical Review*, 52, 221-259. <https://doi.org/10.1007/BF02860996>
- Hennessy, G., Harris, C., Eaton, C., Wright, P., Jackson, E., Goulson, D., & Ratnieks, F. F. (2020). Gone with the wind: effects of wind on honey bee visit rate and

- foraging behaviour. *Animal Behaviour*, 161, 23-31.
<https://doi.org/10.1016/j.anbehav.2019.12.018>
- Hennessey, G., Harris, C., Pirot, L., Lefter, A., Goulson, D., & Ratnieks, F. L. (2021). Wind slows play: Increasing wind speed reduces flower visiting rate in honey bees. *Animal Behaviour*, 178, 87-93.
<https://doi.org/10.1016/j.anbehav.2021.05.022>
- Herrera, C. M., & Pellmyr, O. (2002). Plant–Animal Interactions. An Evolutionary Approach. Blackwell, Oxford.
- Heslop-Harrison, J. S. (1987). Pollen germination and pollen tube growth. In: International review of cytology. Bourne, G.H., Jeon, K.W. and Friedlander, M. (eds.) Vol. 107. Academic Press: 1-78.
- Higashiyama, T., & Takeuchi, H. (2015). The mechanism and key molecules involved in pollen tube guidance. *Annual Review of Plant Biology*, 66(1), 393-413.
<https://doi.org/10.1146/annurev-arplant-043014-115635>
- Hilty, J. A., Keeley, A. T., Lidicker Jr, W. Z., & Merenlender, A. M. (2019). Corridor ecology: linking landscapes for biodiversity conservation and climate adaptation. Island Press.
- Hoe, Y. C., & Wong, S. Y. (2016). Floral biology of *Schismatoglottis baangongensis* (Araceae) in west sarawak, borneo. *Plant Systematics and Evolution*, 302, 1239-1252. <https://doi.org/10.1007/s00606-016-1329-z>
- Holt, W. V., Brown, J. L., & Comizzoli, P. (2014). Reproductive Science as an Essential Component of Conservation Biology. In: Holt, W., Brown, J., Comizzoli, P. (eds) Reproductive Sciences in Animal Conservation. Advances in Experimental Medicine and Biology, vol 753. Springer, New York, NY.
https://doi.org/10.1007/978-1-4939-0820-2_1
- Hooper, D. U., Adair, E. C., Cardinale, B. J., Byrnes, J. E., Hungate, B. A., Matulich, K. L., Gonzalez, A., Duffy, J. E., Gamfeldt, L., & O'Connor, M. I. (2012). A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature*, 486(7401), 105-108. <https://doi.org/10.1038/nature11118>
- Hossain, M. M., Sultana, F., Mostafa, M., Ferdus, H., Rahman, M., Rana, J. A., Islam, S. S., Adhikary, S., Sannal, A., Hosen, M. A. E., Nayeema, J., Emu, N. J., Kundu, M., Biswas, S. K., Farzana, L., & Al Sabbir, M. A. (2024). Plant disease dynamics in a changing climate: impacts, molecular mechanisms, and climate-informed strategies for sustainable management. *Discover Agriculture*, 2(1), 132. <https://doi.org/10.1007/s44279-024-00144-w>
- Humayun, M., Naseem, S., Goodman, R. E., & Ali, Z. (2025). *Broussonetia papyrifera* Pollen Metabolome Insights, Allergenicity, and Dispersal in Response to Climate Change Variables. *Metabolites*, 15(2), 137.
<https://doi.org/10.3390/metabo15020137>
- Iler, A. M., Høye, T. T., Inouye, D. W., & Schmidt, N. M. (2013). Nonlinear flowering responses to climate: are species approaching their limits of phenological

- change?. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1624), 20120489. <https://doi.org/10.1098/rstb.2012.0489>
- Impe, D., Reitz, J., Köpnick, C., Rolletschek, H., Börner, A., Senula, A., & Nagel, M. (2020). Assessment of pollen viability for wheat. *Frontiers in Plant Science*, 10, 1588. <https://doi.org/10.3389/fpls.2019.01588>
- Inouye, D. (2008). Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers.. *Ecology*, 89 2, 353-62 . <https://doi.org/10.1890/06-2128.1>
- Inouye, D. W., & Wielgolaski, F. E. (2025). Phenology at high altitudes. In Phenology: An integrative environmental science (pp. 281-311). Cham: Springer Nature Switzerland.
- Inouye, D. W., Saavedra, F., & Lee-Yang, W. (2003). Environmental influences on the phenology and abundance of flowering by *Androsace septentrionalis* (Primulaceae). *American Journal of Botany*, 90(6), 905-910. <https://doi.org/10.3732/ajb.90.6.905>
- Irudhyaraj, D. F. (2016). Reproductive biology of *Elaeocarpus blascoi* Weibel, and *Hopea ponga* (Dennst.) Mabblerley: Endemic and Endangered Tree species of Southern Western Ghats. Ph. D thesis, The Gandhigram Rural Institute, (Deemed to University), Gandhigram, Dindigul, Tamil Nadu, India.
- Irudhyaraj, D. F., & Ramasubbu, R. (2017). Rediscovery of *Elaeocarpus gaussonii* Weibel: a little known endemic tree of the Western Ghats of Tamil Nadu, India. *Current Science*, 112(12), 2372-2374.
- Irwin, R. E., Adler, L. S., & Brody, A. K. (2004). The dual role of floral traits: pollinator attraction and plant defense. *Ecology*, 85(6), 1503-1511. <https://doi.org/10.1890/03-0390>
- Jacquemart, A. L., Somme, L., Colin, C., & Quinet, M. (2015). Floral biology and breeding system of *Impatiens balfourii* (Balsaminaceae): an exotic species in extension in temperate areas. *Flora-Morphology, Distribution, Functional Ecology of Plants*, 214, 70-75. <https://doi.org/10.1016/j.flora.2015.06.001>
- Jacquemyn, H., De Meester, L., Jongejans, E., & Honnay, O. (2012). Evolutionary changes in plant reproductive traits following habitat fragmentation and their consequences for population fitness. *Journal of Ecology*, 100(1), 76-87. <https://doi.org/10.1111/j.1365-2745.2011.01919.x>
- Jaeger, S., Girvin, C., Demarest, N., & LoPresti, E. (2023). Secondary pollinators contribute to reproductive success of a pink-flowered sand verbena population. *Ecology*, 104(4), e3977. <https://doi.org/10.1002/ecy.3977>
- Jamshed, M., Sankaranarayanan, S., Abhinandan, K., & Samuel, M. A. (2020). Stigma receptivity is controlled by functionally redundant MAPK pathway components in *Arabidopsis*. *Molecular Plant*, 13(11), 1582-1593. <https://doi.org/10.1016/j.molp.2020.08.015>

- Janni, M., Maestri, E., Gulli, M., Marmioli, M., & Marmioli, N. (2024). Plant responses to climate change, how global warming may impact on food security: a critical review. *Frontiers in Plant Science*, 14, 1297569. <https://doi.org/10.3389/fpls.2023.1297569>
- Jayaprakash, P. (2018). Pollen Germination *in vitro*. In: Pollination in plants. Mokwala, P.W.(ed). IntechOpen.
- Jayaprakash, P., & Sarla, N. (2001). Development of an improved medium for germination of *Cajanus cajan* (L.) Millsp. pollen *in vitro*. *Journal of Experimental Botany*, 52(357), 851-855. <https://doi.org/10.1093/jexbot/52.357.851>
- 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. <https://doi.org/10.1111/j.1523-1739.1988.tb00200.x>
- Jensen, A. E. (2008). The roles of seed banks and soil moisture in recruitment of semi-arid floodplain plants: the River Murray, Australia (Doctoral dissertation, University of Adelaide, School of Earth and Environmental Sciences, Discipline of Ecology and Evolutionary Biology).
- Jerome, D., Petry, W., Mooney, K., & Iler, A. (2021). Snow melt timing acts independently and in conjunction with temperature accumulation to drive subalpine plant phenology. *Global Change Biology*, 27, 5054 - 5069. <https://doi.org/10.1111/gcb.15803>
- Jiao, L., Sun, T., Zhang, P., Yang, W., Shao, D., & Zheng, S. (2021). Effect of floral traits mediated by plant-soil feedback on the relationship between plant density and fecundity: Case study of *Tamarix chinensis* in the Yellow River Delta, China. *Global Ecology and Conservation*, 26, e01479. <https://doi.org/10.1016/j.gecco.2021.e01479>
- Johnson, M. A., Harper, J. F., & Palanivelu, R. (2019). A fruitful journey: pollen tube navigation from germination to fertilization. *Annual Review of Plant Biology*, 70(1), 809-837. <https://doi.org/10.1146/annurev-arplant-050718-100133>
- Johnson, S. D. (1996). Pollination, adaptation and speciation models in the Cape flora of South Africa. *Taxon*, 45(1), 59-66. <https://doi.org/10.2307/1222585>
- Joshi, N. K. (2024). Current trends in bee conservation and habitat restoration in different types of anthropogenic habitats. *Frontiers in Ecology and Evolution*, 12, 1401233. <https://doi.org/10.3389/fevo.2024.1401233>
- Jothish, P. S., & Anilkumar, C. (2019). Pollination biology of *Cassine kedarnathii* Sasidh. & Swarup.(Celastraceae), a rare endemic tree species of the western ghats, India. *International Journal of Plant Reproductive Biology*, 11(1), 24-30. <https://doi.org/10.14787/ijprb.2019.11.1>.
- Kaiser-Bunbury, C. N., Mougall, J., Whittington, A. E., Valentin, T., Gabriel, R., Olesen, J. M., & Blüthgen, N. (2017). Ecosystem restoration strengthens

- pollination network resilience and function. *Nature*, 542(7640), 223-227. <https://doi.org/10.1038/nature21071>
- Kalpana, K., Reddy, G. S. V., Chellem, S. R., Rajalakshmi, J. M., Indrani, K., Lavanya, P., & Navya, D. S. (2024). The role of pollinators in enhancing biodiversity and pollination mechanisms: A review. *Uttar Pradesh Journal of Zoology*, 45(13), 226-241. <https://doi.org/10.56557/upjz/2024/v45i134150>
- Kamaraj, N., & Rasappan, K. (2024). Temporal and spatial foraging activity of Indian honey bee (*Apis cerana indica* F.) at different migratory sites. *Sociobiology*, 71(1), e9733-e9733. <https://doi.org/10.13102/sociobiology.v71i1.9733>
- Kampová, A., Nowack, M. K., Fendrych, M., & Vosolsobě, S. (2024). Programmed cell death and stomatal density regulate anther opening in response to ambient humidity. *bioRxiv*, 2024-09. <https://doi.org/10.1101/2024.09.09.612018>
- Kannan, R. (1994). Ecology and Conservation of the Great Pied Hornbill (*Buceros bicornis*) in the Western Ghats of Southern India. Unpublished Ph.D. thesis, University of Arkansas, USA.
- Kanneri, A., Resmi, M. S., Rasack, R. V., & Vivek, P. J. (2025). Comprehensive Analysis of Pollen Viability, *in vitro* Germination, and Self-incompatibility in *Hamelia patens* Jacq. Pollen. *International Journal of Horticultural Science and Technology*, 12(1), 145-156.
- Karron, J. D., Ivey, C. T., Mitchell, R. J., Whitehead, M. R., Peakall, R., & Case, A. L. (2012). New perspectives on the evolution of plant mating systems. *Annals of Botany*, 109(3), 493-503. <https://doi.org/10.1093/aob/mcr319>
- Karunarathne, P., Schedler, M., Martínez, E. J., Honfi, A. I., Novichkova, A., & Hojsgaard, D. (2018). Intraspecific ecological niche divergence and reproductive shifts foster cytotype displacement and provide ecological opportunity to polyploids. *Annals of Botany*, 121(6), 1183-1196. <https://doi.org/10.1093/aob/mcy004>
- Kasi, K. S., & Ramasubbu, R. (2021). Phenological patterns, fruit predation, and seed dispersal in two endangered trees (*Elaeocarpus* spp.) of southern Western Ghats, India. *Journal of Asia-Pacific Biodiversity*, 14(2), 275-282. <https://doi.org/10.1016/j.japb.2021.02.002>
- Kasthurirengan, S., Hong, Y., & Ramachandran, S. (2025). Assessing *Jatropha curcas* pollen viability: a comparative assessment of transgenic and non-transgenic pollen under various environmental conditions using rapid staining technique. *Frontiers in Plant Science*, 16, 1543947. <https://doi.org/10.3389/fpls.2025.1543947>
- Katumo, D. M., Liang, H., Ochola, A. C., Lv, M., Wang, Q. F., & Yang, C. F. (2022). Pollinator diversity benefits natural and agricultural ecosystems, environmental health, and human welfare. *Plant Diversity*, 44(5), 429-435. <https://doi.org/10.1016/j.pld.2022.01.005>

- Kaul, V., & Koul, A. K. (2009). Sex expression and breeding strategy in *Commelina benghalensis* L. *Journal of Biosciences*, 34, 977-990. <https://doi.org/10.1007/s12038-009-0112-5>
- Kazan, K., & Lyons, R. (2016). The link between flowering time and stress tolerance. *Journal of Experimental Botany*, 67, 1, 47-60. <https://doi.org/10.1093/jxb/erv441>
- Kearns, C. A. (2001). North American dipteran pollinators: assessing their value and conservation status. *Conservation Ecology*, 5(1).
- Kearns, C. A., & Inouye, D. W. (1993). Techniques for Pollination Biologists, University Press of Colorado, Niwot, USA.
- Kearns, C. A., & Inouye, D. W. (1997). Pollinators, flowering plants, and conservation biology. *Bioscience*, 47(5), 297-307. <https://doi.org/10.2307/1313191>
- Kehrberger, S., & Holzschuh, A. (2019). How does timing of flowering affect competition for pollinators, flower visitation and seed set in an early spring grassland plant?. *Scientific Reports*, 9(1), 15593. <https://doi.org/10.1038/s41598-019-51916-0>
- Keller, J., & Shea, K. (2020). Warming and shifting phenology accelerate an invasive plant life cycle. *Ecology*, 102. <https://doi.org/10.1002/ecy.3219>
- Kendall, L., & Nicholson, C. C. (2025). Pollination Across the Diel Cycle: A Global Meta-Analysis. *Ecology Letters*, 28(1), e70036. <https://doi.org/10.1111/ele.70036>
- Kevan, P. G. (2005). Advertisement in flowers. In: Practical Pollination Biology. Dafni, A., Kevan, P.G. and Husband, B.C. (eds). Enviro quest, Cambridge.
- Khan, S. A., Teja, K. S. S., Panigrahi, C. K., Kumar, A., & Bhavana, P. (2023a) Conservation of Pollinators and Natural Resources in Agriculture. Smart Agricultural Technologies for Sustainable Crop Production.
- Khan, S., Kumari, P., & Verma, S. (2023b). Ambophily in *Olea ferruginea*: A transitional state in the pollination syndrome. *Plant Biosystems*, 157(2), 221-232. <https://doi.org/10.1080/11263504.2022.2100497>
- Khanduri VP, Sharma CM, Kumar KS, Ghildiyal SK (2013) Annual variation in flowering phenology, pollination, mating system, and pollen yield in two natural populations of *Schima wallichii* (DC.) Korth. *Scientific World Journal*, 2013(1):350157. <https://doi.org/10.1155/2013/350157>
- 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. (2012). 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. <https://doi.org/10.1111/j.1756-1051.2011.01157.x>
- Khanduri, V. P., & Kumar, K. S. (2017a). Pollen production and release in *Mesua ferrea* Linn.(Guttiferae): a spatio-temporal pattern. *Aerobiologia*, 33, 13-21. <https://doi.org/10.1007/s10453-016-9446-2>

- Khanduri, V. P., & Kumar, K. S. (2017b). Reproductive effort and success in *Bombax ceiba* L. in a tropical forest of Mizoram, Indo-Burma region of North-East India. *Brazilian Journal of Botany*, 40, 157-166. <https://doi.org/10.1007/s40415-016-0327-2>
- Khanduri, V. P., Kumar, K. S., & Sharma, C. M. (2015a). Role of pollen production in mating success in some tropical tree species. *Brazilian Journal of Botany*, 38, 107-112. <https://doi.org/10.1007/s40415-014-0114-x>
- Khanduri, V. P., Kumar, K. S., Sharma, C. M., Riyal, M. K., & Kar, K. (2019). Pollen limitation and seed set associated with year-to-year variation in flowering of *Gmelina arborea* in a natural tropical forest. *Grana*, 58(2), 133-143. <https://doi.org/10.1080/00173134.2018.1536164>
- Khanduri, V. P., Sharma, C. M., Kumar, K. S., & Kar, K. (2015b). Biannual pollen production in *Lagerstroemia speciosa* (L.) Pers.(Lythraceae). *Grana*, 54(1), 26-36. <https://doi.org/10.1080/00173134.2014.946088>
- 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. <https://doi.org/10.1007/s11676-018-0779-2>
- Khatun, S., & Flowers, T. J. (1995). The estimation of pollen viability in rice. *Journal of Experimental Botany*, 46(1), 151-154. <https://doi.org/10.1093/jxb/46.1.151>
- Kılıç, T., Sinanoğlu, E., Kırbay, E., Kazaz, S., & Ercişli, S. (2024). Determining appropriate methods for estimating pollen viability and germination rates in *lisianthus*. *Acta Scientiarum Polonorum Hortorum Cultus*, 23(3), 33-42. <https://doi.org/10.24326/asphc.2024.5378>
- Kim, H. J., Hong, J. K., Kim, S. C., Oh, S. H., & Kim, J. H. (2011). Plant phenology of threatened species for climate change in sub-alpine zone of Korea-especially on the summit area of Mt. Deogyusan. *Korean Journal of Plant Resources*, 24(5), 549-556.
- Knudsen, J. T., & Gershenzon, J. (2006). The chemical diversity of floral scent. In: Biology of floral scent. Dudareva, N. and Pichersky, E., (eds) CRC Press, Boca Raton. 27-44.
- Koski, M. H. (2023). Pollinators exert selection on floral traits in a pollen-limited, narrowly endemic spring ephemeral. *American Journal of Botany*, 110(1), e16101. <https://doi.org/10.1002/ajb2.16101>
- Krishnakumar, N., Parthiban, K. T., & Umesh Kanna, S. (2018). Identification of pollinators for good quality seed productions in sandal wood (*Santalum album* L.). *Journal of Entomology and Zoology Studies*, 6(3), 1467-1470.
- Kubota, T. Y., Hallsworth, J. E., da Silva, A. M., Moraes, M. L., Cambuim, J., Corseuil, C. W., & Sebbenn, A. M. (2024). Pollen dispersal and mating patterns determine resilience for a large-yet-fragmented population of *Cariniana*

- estrellensis*. *Conservation Genetics*, 25(1), 117-132.
<https://doi.org/10.1007/s10592-023-01557-8>
- Kumar KS, Tripathi SK, Khanduri VP (2023) Phenological patterns of tropical trees in relation to climatic factors in a mountain moist forest of Indo-Burma hotspot region. *Vegetos* 36:1070-1079. <https://doi.org/10.1007/s42535-022-00474-4>
- Kumar, A., Rajwar, N., & Tonk, T. (2024). Climate Change Effects on Plant-Pollinator Interactions, Reproductive Biology and Ecosystem Services. In: Singh, H. (eds) *Forests and Climate Change*. Springer, Singapore. https://doi.org/10.1007/978-981-97-3905-9_5
- Kumar, K. S, Khanduri, V. P, Kar, K., Sharma, C. M, & Riyal, M. K. (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. <http://jast.modares.ac.ir/article-23-2964-en.html>
- Kumar, K. S., Khanduri, V. P., & Tripathi, S. K. (2021). Reproductive adaptations and the availability of pollinating vectors in white Indian teak (*Gmelina arborea* Roxb.) in tropical rain forest of Indo-Burma Hotspot. *Trees, Forests and People*, 3, 100058. <https://doi.org/10.1016/j.tfp.2020.100058>
- Kumar, K. S., Tripathi, S. K., & Khanduri, V. P. (2023). Phenological patterns of tropical trees in relation to climatic factors in a mountain moist forest of Indo-Burma hotspot region. *Vegetos*, 36(3), 1070-1079. <https://doi.org/10.1007/s42535-022-00474-4>
- Kumar, S. S., & Raju, A. J. S. (2021). Reproductive ecology of *Mesua ferrea*, a tropical evergreen tree species from India. *Phytologia Balcanica*, 27(1), 3-22.
- Kundu, B., & Kumar, R. (2024). Enhancing Crop Resilience to Climate Change through Biochar: A Review. *International Journal of Environment and Climate Change*, 14(6), 170-184.
- Kushwaha, C. P., & Singh, K. P. (2005). Diversity of leaf phenology in a tropical deciduous forest in India. *Journal of Tropical Ecology*, 21(1), 47-56. <https://doi.org/10.1017/S0266467404002032>
- Kwak, M. M., & Bekker, R. M. (2006). Ecology of plant reproduction: extinction risks and restoration perspectives of rare plant species. In: *Plant-pollinator interactions: from specialization to generalization*. Waser, N. M. and Ollerton, J. (eds). University of Chicago Press, Chicago, 362-386.
- Lalrinmawia. (2024). Trends and variability of rainfall in Mizoram. *Disaster Advances*, 17(12), 44-50. <https://doi.org/10.25303/1712da044050>
- Lander, T. A., Harris, S. A., Cremona, P. J., & Boshier, D. H. (2019). Impact of habitat loss and fragmentation on reproduction, dispersal and species persistence for an endangered Chilean tree. *Conservation Genetics*, 20, 973-985. <https://doi.org/10.1007/s10592-019-01187-z>
- Lau, J. Y., Pang, C. C., Ramsden, L., & Saunders, R. M. (2016). Reproductive resource partitioning in two sympatric *Goniothalamus* species (Annonaceae) from

- Borneo: floral biology, pollinator trapping and plant breeding system. *Scientific Reports*, 6(1), 35674. <https://doi.org/10.1038/srep35674>
- Leach, T. S. (2022). The Role of Pre-and Post-Spawning Temperature Stress on Fertilization Dynamics within Santa Barbara Channel Sea Urchin Species. University of California, Santa Barbara.
- Leclerc, M. A., Gibernau, M., & Pincebourde, S. (2024). Pollination-related plant traits under environmental changes: Seasonal and daily mismatches produce temporal constraints. *Functional Ecology*, 1-11. <https://doi.org/10.1111/1365-2435.14674>
- Lee, H., & Kang, H. (2018). Temperature-driven changes of pollinator assemblage and activity of *Megaleranthis saniculifolia* (Ranunculaceae) at high altitudes on Mt. Sobaeksan, South Korea. *Journal of Ecology and Environment*, 42(1), 1-7. <https://doi.org/10.1186/s41610-018-0092-1>
- Lee, Y. D., Yokoi, T., & Nakazawa, T. (2024). A pollinator crisis can decrease plant abundance despite pollinators being herbivores at the larval stage. *Scientific Reports*, 14(1), 18523. <https://doi.org/10.1038/s41598-024-69537-7>
- Lesmes-Vesga, R. A., Chaparro, J. X., Sarkhosh, A., Ritenour, M. A., Cano, L. M., & Rossi, L. (2021). Effect of propagation systems and indole-3-butyric acid potassium salt (K-IBA) concentrations on the propagation of peach rootstocks by stem cuttings. *Plants*, 10(6), 1151. <https://doi.org/10.3390/plants10061151>
- Lewis, S., Phillips, R. A., Burthe, S. J., Wanless, S., & Daunt, F. (2015). Contrasting responses of male and female foraging effort to year-round wind conditions. *Journal of Animal Ecology*, 84(6), 1490-1496. <https://doi.org/10.1111/1365-2656.12419>
- Li T, Liu X, Li Z, Ma H, Wan Y, Liu X, Fu L (2018) Study on reproductive biology of *Rhododendron longipedicellatum*: A newly discovered and special threatened plant surviving in limestone habitat in Southeast Yunnan, China. *Frontiers in Plant Science*, 9:33. <https://doi.org/10.3389/fpls.2018.00033>
- Li, M., Jiang, F., Huang, L., Wang, H., Song, W., Zhang, X., Zhang, Y., & Niu, L. (2023). Optimization of in vitro germination, viability tests and storage of *Paeonia ostii* pollen. *Plants*, 12(13), 2460. <https://doi.org/10.3390/plants12132460>
- Li, X. X., Wang, H., Gituru, R. W., Guo, Y. H., & Yang, C. F. (2014). Pollen packaging and dispensing: adaption of patterns of anther dehiscence and flowering traits to pollination in three *Epimedium* species. *Plant Biology*, 16(1), 227-233. <https://doi.org/10.1111/plb.12040>
- Lieth, H. (1974). Phenology and seasonality modeling (Vol. 8). Springer Science & Business Media - Verlag, Berlin.
- Linder, H. P. (1998). Morphology and the evolution of wind pollination. In: Reproductive Biology. Owens, S.J. and Rudall, P.J. (eds). Royal Botanic Gardens, Kew, UK. pp. 123-135
- Linskens, H. F. (1967). Pollen. *Handbuch der pflanzenphysiologie* XVIII, 368-406.

- Listabarth, C. (2001). Palm pollination by bees, beetles and flies: why pollinator taxonomy does not matter. The case of *Hyospathe elegans* (Arecaceae, Arecoideae, Areceae, Euterpeinae). *Plant Species Biology*, 16(2), 165-181. <https://doi.org/10.1046/j.1442-1984.2001.00061.x>
- Liu, U., Cossu, T. A., Davies, R. M., Forest, F., Dickie, J. B., & Breman, E. (2020). Conserving orthodox seeds of globally threatened plants ex situ in the Millennium Seed Bank, Royal Botanic Gardens, Kew, UK: the status of seed collections. *Biodiversity and Conservation*, 29(9), 2901-2949. <https://doi.org/10.1007/s10531-020-02005-6>
- Liu, X., Zhou, L., Du, C., Wang, S., Chen, H., Xu, W., Yang, Z., & Liang, Q. (2024). Effects of Pollen Germination and Pollen Tube Growth under Different Temperature Stresses in Mango (*Mangifera indica* L.) by Metabolome. *Metabolites*, 14(10), 543. <https://doi.org/10.3390/metabo14100543>
- López-Vázquez, K., Lara, C., Corcuera, P., & Castillo-Guevara, C. (2024a). Temporal Shifts in Flower-Visiting Butterfly Communities and Their Floral Resources along a Vegetation Type Altered by Anthropogenic Factors. *Forests*, 15(9), 1668. <https://doi.org/10.3390/f15091668>
- López-Vázquez, K., Lara, C., Corcuera, P., Castillo-Guevara, C., & Cuautle, M. (2024b). The human touch: a meta-analysis of anthropogenic effects on plant-pollinator interaction networks. *PeerJ*, 12, e17647. <https://doi.org/10.7717/peerj.17647>
- Lowe, A. J., Boshier, D., Ward, M., Bacles, C. F. E., & Navarro, C. (2005). Genetic resource impacts of habitat loss and degradation; reconciling empirical evidence and predicted theory for neotropical trees. *Heredity*, 95(4), 255-273. <https://doi.org/10.1038/sj.hdy.6800725>
- Lu, X., Ma, R., & Sun, K. (2008). Determination of the wind pollination distances and flowering characteristics of *Hippophae rhamnoides* L. ssp. *sinensis* Rousi (Elaeagnaceae). *Acta Ecologica Sinica*, 28, 2518-2525.
- Luz, C. F. D., Maki, E. S., Horak-Terra, I., Vidal-Torrado, P., & Mendonça Filho, C. V. (2013). Pollen grain morphology of Fabaceae in the special protection area (SPA) Pau-de-Fruta, Diamantina, Minas Gerais, Brazil. *Anais da Academia Brasileira de Ciências*, 85, 1329-1344. <https://doi.org/10.1590/0001-3765201380511>
- Ma, W. H., Wu, W. Q., Song, H. L., Lei, J., & Li, L. X. (2025). Effects of different pollination methods on tomato fruits' quality and metabolism. *Frontiers in Plant Science*, 16, 1560186. <https://doi.org/10.3389/fpls.2025.1560186>
- Mabuza, P. G. B. (2024). Understanding disturbance, vegetation density, seed banks and pollination for the conservation of *Protea curvata* (Doctoral dissertation, University of the Witwatersrand, Johannesburg).

- Macior, L. W. (1967). Pollen-foraging behavior of *Bombus* in relation to pollination of nototribic flowers. *American Journal of Botany*, 54(3), 359-364. <https://doi.org/10.1002/j.1537-2197.1967.tb06930.x>
- Maita, S., & Sotomayor, C. (2015). The effect of three plant bioregulators on pollen germination, pollen tube growth and fruit set in almond [*Prunus dulcis* (Mill.) DA Webb] cvs. Non Pareil and Carmel. *Electronic Journal of Biotechnology*, 18(5), 381-386. <https://doi.org/10.1016/j.ejbt.2015.07.004>
- Maldonado, M., Fornoni, J., Boege, K., Pérez Ishiwara, R., Santos-Gally, R., & Domínguez, C. A. (2023). The role of within-plant variation in nectar production: an experimental approach. *Annals of Botany*, 132(1), 95-106. <https://doi.org/10.1093/aob/mcad082>
- Manikandan, G. (2016). Reproductive Biology of *Garcinia imberti* Bourd. And *G. travancorica* Bedd: Endemic and Endangered Tree Species from Agasthyamalai Biosphere Reserve, Ph. D. Thesis, The Gandhigram Rural Institute- Deemed University, Gandhigram, Tamil Nadu, India.
- Manjula, K. K., & Nair, B. R. (2018). Reproductive biology of *Eleutherine bulbosa* (Miller) urban (Iridaceae). *International Journal of Plant Reproductive Biology*, 10(1), 52-58.
- Marbaniang, E., Venugopal, N., Verma, S., Raina, R., Khajuria, A., & Gautam, K. (2018). Floral Biology and Embryological Studies are Important for Conservation of Threatened Plants Having Reproductive Bottlenecks: A Case Study of *Illicium griffithii* Hook. f. & Thomson. *Current Science*, 114, 576-587. <https://doi.org/10.18520/CS/V114/I03/576-587>
- Martén-Rodríguez, S., Rodríguez-Martén, V., Cristóbal-Pérez, E. J., Díaz-Infante, S., & Quesada, M. (2024). Vegetative traits, floral biology, and mutualistic interactions in the tropical mountain shrub *Ribes ciliatum* (Grossulariaceae). *Flora*, 152618. <https://doi.org/10.1016/j.flora.2024.152618>
- Martínez-Gómez, J., Park, S., Hartogs, S. R., Soza, V. L., Park, S. J., & Di Stilio, V. S. (2023). Flower morphology as a predictor of pollination mode in a biotic to abiotic pollination continuum. *Annals of Botany*, 132(1), 61-76. <https://doi.org/10.1093/aob/mcad069>
- Marutani, M., Sheffer, R. D., & Kamemoto, H. (1993). Cytological analysis of *Anthurium andraeanum* (Araceae), its related taxa and their hybrids. *American Journal of Botany*, 80(1), 93-103. <https://doi.org/10.1002/j.1537-2197.1993.tb13772.x>
- Maschinski, J., & Albrecht, M. A. (2017). Center for Plant Conservation's Best Practice Guidelines for the reintroduction of rare plants. *Plant Diversity*, 39(6), 390-395. <https://doi.org/10.1016/j.pld.2017.09.006>
- Matsui, T., & Hasegawa, T. (2019). Effect of long anther dehiscence on seed set at high temperatures during flowering in rice (*Oryza sativa* L.). *Scientific Reports*, 9(1), 20363. <https://doi.org/10.1038/s41598-019-56792-2>

- Matsui, T., Omasa, K., & Horie, T. (1999). Mechanism of anther dehiscence in rice (*Oryza sativa* L.). *Annals of Botany*, 84(4), 501-506. <https://doi.org/10.1006/anbo.1999.0943>
- Maués, M. M., de Oliveira, P. E. A., & Kanashiro, M. (2008). Pollination biology in *Jacaranda copaia* (Aubl.) D. Don.(Bignoniaceae) at the " floresta nacional do tapajós", central amazon, brazil. *Brazilian Journal of Botany*, 31, 517-527. <https://doi.org/10.1590/S0100-84042008000300015>
- McCall, A. C., & Irwin, R. E. (2006). Florivory: the intersection of pollination and herbivory. *Ecology Letters*, 9(12), 1351-1365. <https://doi.org/10.1111/j.1461-0248.2006.00975.x>
- Medan, D., & Basilio, A. M. (2001). Reproductive biology of *Colletia spinosissima* (Rhamnaceae) in Argentina. *Plant Systematics and Evolution*, 229, 79-89. <https://doi.org/10.1007/s006060170019>
- Mendes, S. B., Timóteo, S., Loureiro, J., & Castro, S. (2022). The impact of habitat loss on pollination services for a threatened dune endemic plant. *Oecologia*, 198(1), 279-293. <https://doi.org/10.1007/s00442-021-05070-y>
- Menon, D., Behera, D., & Ayyappan, N. (2024). Phenological trends and associated climate drivers of a tree community in lowland dipterocarp forest, Western Ghats, India. *International Journal of Biometeorology*, 1-17. <https://doi.org/10.1007/s00484-024-02802-6>
- Menon, S. A. (1993). Ecology and Conservation of the endangered Lion-tailed Macaque, *Macaca silenus*, in the landscape mosaic of Western Ghats. Ph.D. thesis, Ohio State University, USA. 11.
- Michalski, S. G., & Durka, W. (2009). Pollination mode and life form strongly affect the relation between mating system and pollen to ovule ratios. *New Phytologist*, 183(2), 470-479. <https://doi.org/10.1111/j.1469-8137.2009.02861.x>
- Mishra, S. P., Puhan, J. P., & Mishra, S. (2021). Probing the crisis of regional connectivity instigated by the natural disasters, Mizoram, India. *International Journal of Environment and Climate Change*, 11, 39-59.
- Mittelbach, G., & McGill, B. (2019). Community Ecology. Oxford University Press. <https://doi.org/10.4135/9781446247501.n768>
- Miyake, T., & Yahara, T. (1999). Theoretical evaluation of pollen transfer by nocturnal and diurnal pollinators: when should a flower open?. *Oikos*, 233-240. <https://doi.org/10.2307/3546441>
- Mohan, J., Wadgyamar, S., Winkler, D., Anderson, J., Frankson, P., Hannifin, R., Benavides, K., Kueppers, L., & Melillo, J. (2019). Plant reproductive fitness and phenology responses to climate warming: Results from native populations, communities, and ecosystems. *Ecosystem Consequences of Soil Warming*. <https://doi.org/10.1016/B978-0-12-813493-1.00004-1>
- Mohebi, Z., & Mirzaei, H. (2021). Biodiversity and integration of ecological characteristics of species in spatial pattern analysis. *Global Journal of*

- Environmental Science and Management*, 7(3), 473-484.
<https://doi.org/10.22034/GJESM.2021.03.10>
- Moles, A. T., Dalrymple, R. L., Raghu, S., Bonser, S. P., & Ollerton, J. (2022). Advancing the missed mutualist hypothesis, the under-appreciated twin of the enemy release hypothesis. *Biology Letters*, 18(10), 20220220.
<https://doi.org/10.1098/rsbl.2022.0220>
- Molina, R. T., Rodríguez, A. M., Palaciso, I. S., & López, F. G. (1996). Pollen production in anemophilous trees. *Grana*, 35(1), 38-46.
<https://doi.org/10.1080/00173139609430499>
- Møller, C. (2023). Adaptation of understory herbs to forest management (Doctoral dissertation, Universitätsbibliothek Johann Christian Senckenberg).
- Monika, M. K., & Bhatnagar, A. K. (2007). Plant reproductive biology studies crucial for conservation. *Current Science*, 92(9), 1207.
- Monteiro, B. L., Souza, C. S., Maruyama, P. K., Camargo, M. G. G., & Morellato, L. P. C. (2024). Using Plant-Pollinator Network to Identify Priority Species for Conservation in a Biodiversity Hotspot. Available at SSRN 4928917.
- Moraes, I. C. R. D., Pinto-Maglio, C. A. F., & Lombello, R. A. (2009). Biologia da reprodução e citologia de *Hypericum brasiliense* Choisy (Hypericaceae). *Brazilian Journal of Botany*, 32, 539-544. <https://doi.org/10.1590/S0100-84042009000300013>
- Moreira-Hernández, J. I., & Muchhala, N. (2019). Importance of pollinator-mediated interspecific pollen transfer for angiosperm evolution. *Annual Review of Ecology, Evolution, and Systematics*, 50(1), 191-217.
<https://doi.org/10.1146/annurev-ecolsys-110218-024804>
- Morellato, L. P. C., Talora, D. C., Takahasi, A., Bencke, C. C., Romera, E. C., & Zipparro, V. B. (2000). Phenology of Atlantic rain forest trees: a comparative study 1. *Biotropica*, 32(4b), 811-823. <https://doi.org/10.1111/j.1744-7429.2000.tb00620.x>
- Morellato, L., Alberton, B., Alvarado, S., Borges, B., Buisson, E., Camargo, M., Cancian, L., Carstensen, D., Escobar, D., De Paula Leite, P., Mendoza, I., Rocha, N., Soares, N., Silva, T., Staggemeier, V., Streher, A., Da Cunha Vargas, B., & Peres, C. (2016). Linking plant phenology to conservation biology. *Biological Conservation*, 195, 60-72. <https://doi.org/10.1016/J.BIOCON.2015.12.033>
- Mousavi, F., Oteros, J., Shahali, Y., & Carinanos, P. (2024). Impacts of climate change on allergenic pollen production: a systematic review and meta-analysis. *Agricultural and Forest Meteorology*, 349, 109948.
<https://doi.org/10.1016/j.agrformet.2024.109948>
- Muchhala, N., Johnsen, S., & Smith, S. D. (2014). Competition for hummingbird pollination shapes flower color variation in Andean Solanaceae. *Evolution*, 68(8), 2275-2286. <https://doi.org/10.1111/evo.12441>

- Mulder, C. P., Iles, D. T., & Rockwell, R. F. (2017). Increased variance in temperature and lag effects alter phenological responses to rapid warming in a subarctic plant community. *Global Change Biology*, 23(2), 801-814. <https://doi.org/10.1111/gcb.13386>
- Muniyan, S., & Lallawmzuali, M. (2024). Probability analysis of annual and monthly rainfall in Mizoram, India: evaluating goodness of fit and identifying best probability distributions. *Mausam*, 75(3), 815-822. <https://doi.org/10.54302/mausam.v75i3.6250>
- Muñoz-Gallego, R., Traveset, A., Beltrán, R., & Hervías-Parejo, S. (2025). Mixed mating system and intraspecific variation in lizard pollination of *Withania frutescens* (L.) Pauquy. *AoB Plants*, 17(2), plaf008. <https://doi.org/10.1093/aobpla/plaf008>
- Murúa, M., Espíndola, A., & Pérez, F. (2020). Self-compatibility not associated with morphological or genetic diversity reduction in oil-rewarding calceolaria species. *Plants*, 9(10), 1377. <https://doi.org/10.3390/plants9101377>
- Mustard, M. J., Nelson, R. O., & Liu, S. Y. (1953). Observations of floral biology and fruitsetting in lychee varieties. In *Proceedings of the Florida State Horticultural Society* (Vol. 66, pp. 212-219).
- Nadarajan, S., & Pujari, S. S. (2019). Phenological patterns of an endangered tree species *Syzygium caryophyllatum* in Western Ghats, India: Implication for conservation. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, 89, 1275-1281. <https://doi.org/10.1007/s40011-018-1044-3>
- Nanda, A. N. A., Murthy, Y. L. K., & Suresh, H. S. (2013). Canopy trees leaf phenology in tropical dry deciduous and evergreen forests of Bhadra Wildlife Sanctuary Karnataka, India. *African Journal of Plant Science*, 7(5), 170-175.
- Nanda, A., Suresh, H. S., & Krishnamurthy, Y. L. (2014). Phenology of a tropical dry deciduous forest of Bhadra wildlife sanctuary, southern India. *Ecological Processes*, 3, 1-12. <https://doi.org/10.1186/2192-1709-3-1>
- Narayanan, N., Hale, K. R., Koffel, T., & McPeck, S. J. (2023). Theoretical Advances in the Ecology and Evolution of Mutualistic Interactions—Review of a Symposium (SYMP 14) Organized at ESA+ CSEE 2022 Joint Meeting. *Bulletin of the Ecological Society of America*, 104(2), 1-9. <https://www.jstor.org/stable/48720578>
- Nasrallah, J. B. (2024). Stop and go signals at the stigma–pollen interface of the Brassicaceae. *Plant Physiology*, 195(4), 3138. <https://doi.org/10.1093/plphys/kiae242>
- Navarro, L., Guitian, J., & Guitian, P. (1993). Reproductive biology of *Petrocoptis grandiflora* Rothm.(Caryophyllaceae), a species endemic to Northwest Iberian Peninsula. *Flora*, 188, 253-261. [https://doi.org/10.1016/S0367-2530\(17\)32274-0](https://doi.org/10.1016/S0367-2530(17)32274-0)

- Nayak, K. G., & Davidar, P. (2010). Pollination and breeding systems of woody plant species in tropical dry evergreen forests, southern India. *Flora-Morphology, Distribution, Functional Ecology of Plants*, 205(11), 745-753. <https://doi.org/10.1016/j.flora.2009.12.041>
- Nebot, A., Cogoni, D., Fenu, G., & Bacchetta, G. (2016). Floral biology and breeding system of the narrow endemic *Dianthus morisianus* Vals.(Caryophyllaceae). *Flora*, 219, 1-7. <https://doi.org/10.1016/j.flora.2015.12.004>
- Nepi, M., & Franchi, G. G. (2000). Cytochemistry of mature angiosperm pollen. *Pollen and Pollination*, 45-62. https://doi.org/10.1007/978-3-7091-6306-1_3
- 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*, 141-159. <https://doi.org/10.2307/2388804>
- Nicolson, S. W. & Thornburg, R. W. (2007). Nectar chemistry. In: Nicolson S. et al (eds.) *Nectaries and nectar*, Springer, Berlin/Heidelberg/New York.
- Nicolson, S. W. (2022). Sweet solutions: nectar chemistry and quality. *Philosophical Transactions of the Royal Society B*, 377(1853), 20210163. <https://doi.org/10.1098/rstb.2021.0163>
- Nocentini, D., Pacini, E., Guarnieri, M., & Nepi, M. (2012). Flower morphology, nectar traits and pollinators of *Cerintho major* (Boraginaceae-Lithospermeae). *Flora-Morphology, Distribution, Functional Ecology of Plants*, 207(3), 186-196. <https://doi.org/10.1016/j.flora.2012.01.004>
- Nortin, J. D. (1966). Testing of plum pollen viability with tetrazolium salts. In: *Proceeding of the American society for horticultural science*. 89:132- 134.
- Nunes, C. E., Amorim, F. W. D., Mayer, J. L. S., & Sazima, M. (2016). Pollination ecology of two species of *Elleanthus* (Orchidaceae): novel mechanisms and underlying adaptations to hummingbird pollination. *Plant Biology*, 18(1), 15-25. <https://doi.org/10.1111/plb.12312>
- Núñez-Cruz, A., Meave, J. A., & Bonfil, C. (2018). Reproductive phenology and seed germination in eight tree species from a seasonally dry tropical forest of Morelos, Mexico: Implications for Community-Oriented Restoration and Conservation. *Tropical Conservation Science*, 11, 1-14. <https://doi.org/10.1177/1940082917749946>
- Obregon, D., Guerrero, O. R., Stashenko, E., & Poveda, K. (2021). Natural habitat partially mitigates negative pesticide effects on tropical pollinator communities. *Global Ecology and Conservation*, 28, e01668. <https://doi.org/10.1016/j.gecco.2021.e01668>
- Ogilvie, J. E., & Thomson, J. D. (2015). Male bumble bees are important pollinators of a late-blooming plant. *Arthropod-Plant Interactions*, 9(2), 205-213. <https://doi.org/10.1007/s11829-015-9368-x>
- Oliveira, I. S. D. S., Souza, V. C. D., Santos, S. B. D. C., Almeida, J. N. D. R., Henrique, J. D. S., Costa, P. M. D. A., Silva, J. H. C. S., Cassimiro, C. A. L., de

- Lucena, C. É. A., & Melo, T. D. S. (2019). Floral Biology and Pollen Viability of *Passiflora edulis* Sims. *Journal of Experimental Agriculture International*, 41(1), 1-9.
- Oliveira, M. D. S. P. D., Maués, M. M., & Kalume, M. A. D. A. (2001). Viabilidade de pólen *in vivo* e *in vitro* em genótipos de açaizeiro. *Acta Botânica Brasilica*, 15, 27-33. <https://doi.org/10.1590/S0102-33062001000100004>
- Ollerton, J., Winfree, R., & Tarrant, S. (2011). How many flowering plants are pollinated by animals?. *Oikos*, 120(3), 321-326. <https://doi.org/10.1111/j.1600-0706.2010.18644.x>
- Opler, P. A. (1983). Nectar production in a tropical ecosystem. In: The biology of nectaries. Bentley, B. and Elias, T. (eds.). Columbia University Press. New York. 30-79.
- 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. *Journal of Ecology*, 68(1), 167-188. <https://doi.org/10.2307/2259250>
- Osborn MM, Kevan PG, Lane MA (1988) Pollination biology of *Opuntia polyacantha* and *Opuntia phaeacantha* (Cactaceae) in southern Colorado. *Plant Systematics and Evolution*, 159:85-94. <https://doi.org/10.1007/BF00937427>
- Otieno, B. A., & Namiripo, D. B. (2020). The role of pollinators in plant reproduction: their ecological interactions, evolutionary adaptations, and the impact on biodiversity conservation. *Advances in Herbal Research*, 3(1), 1-5. <https://doi.org/10.25163/ahi.319923>
- Ottaviano, E., & Mulcahy, D. L. (1989). Genetics of angiosperm pollen. *Advances in Genetics*, 26, 1-64. [https://doi.org/10.1016/S0065-2660\(08\)60222-9](https://doi.org/10.1016/S0065-2660(08)60222-9)
- Owens, A. C., & Lewis, S. M. (2018). The impact of artificial light at night on nocturnal insects: a review and synthesis. *Ecology and Evolution*, 8(22), 11337-11358. <https://doi.org/10.1002/ece3.4557>
- Pacini, E. & Nepi, M. (2007). Nectar production and presentation. In: Nectaries and Nectar. Nicolson, S.W., Nepi, M., Pacini, E. (eds.). Springer, Dordrecht, Netherlands, pp. 167–214.
- Pacini, E., & Dolferus, R. (2019). Pollen developmental arrest: maintaining pollen fertility in a world with a changing climate. *Frontiers in Plant Science*, 10, 679. <https://doi.org/10.3389/fpls.2019.00679>
- Paggi, G., Silveira, L., Zanella, C., Bruxel, M., Bered, F., Kaltchuk-Santos, E., & Palma-Silva, C. (2013). Reproductive system and fitness of *Vriesea friburgensis*, a self-sterile bromeliad species. *Plant Species Biology*, 28, 169-176. <https://doi.org/10.1111/J.1442-1984.2012.00374.X>
- Panda, P. C., Kumar, S., Singh, J. P., Gajurel, P., Kamila, P. K., Kashung, S., Kulloli, R. N., Singh, P. P., Adhikari, D., & Barik, S. K. (2018). Improving

- macropropagation and seed germination techniques for conservation of threatened species. *Current Science*, 114(3), 562-566.
- Pang, S., Pan, K., Wang, Y., Li, W., Zhang, L., & Chen, Q. (2012). Floral morphology and reproductive biology of *Dendrobium jiajiangense* (Orchidaceae) in Mt. Fotang, southwestern China. *Flora-Morphology, Distribution, Functional Ecology of Plants*, 207(6), 469-474. <https://doi.org/10.1016/j.flora.2012.02.008>
- Parachnowitsch, A. L., Manson, J. S., & Sletvold, N. (2019). Evolutionary ecology of nectar. *Annals of Botany*, 123(2), 247-261. <https://doi.org/10.1093/aob/mcy132>
- Parra-Tabla, V., & Vargas, C. F. (2007). Flowering synchrony and floral display size affect pollination success in a deceit-pollinated tropical orchid. *Acta Oecologica*, 32(1), 26-35. <https://doi.org/10.1016/j.actao.2007.02.002>
- Patil, P. B., Rajah, R. A., Bora, N. R., Brahma, D., Krishnan, S. N., Vasanth, V., Nath, I., Dutta, P. L., Nitish, G., & Prabhakar, S. J. M. (2023). Pollination ecology: Understanding plant-pollinator relationships. *International Journal of Research in Agronomy*, 7(5): 101-105. <https://doi.org/10.33545/2618060X.2024.v7.i5b.654>
- Pearse A. G. E. (1972). *Histochemistry, Theoretical and Applied*, 2nd ed. Churchill Livingstone, Edinburgh.
- Pena, R. A. R., & Wolfe, A. D. (2023). Effect of climate, anther morphology and pollination syndrome on pollen availability in *Penstemon*. *Journal of Pollination Ecology*, 35, 296-311. [https://doi.org/10.26786/1920-7603\(2023\)703](https://doi.org/10.26786/1920-7603(2023)703)
- Pesendorfer, M. B., Bogdziewicz, M., Koenig, W. D., Ledwoń, M., & Żywiec, M. (2019). Declining fruit production before death in a widely distributed tree species, *Sorbus aucuparia* L. *Annals of Forest Science*, 76, 1-7. <https://doi.org/10.1007/s13595-018-0791-x>
- Petanidou, T., Goethals, V., & Smets, E. (2000). Nectary structure of Labiatae in relation to their nectar secretion and characteristics in a Mediterranean shrub community—Does flowering time matter?. *Plant Systematics and Evolution*, 225, 103-118. <https://doi.org/10.1007/BF00985461>
- Peterson, M. L. (2015). *Ecological divergence in flowering plants: Niche expansion, selection, and reproductive isolation*. University of California, Santa Cruz.
- Peterson, R., Slovin, J. P., & Chen, C. (2010). A simplified method for differential staining of aborted and non-aborted pollen grains. *International Journal of Plant Biology*, 1(2), 66-69. <https://doi.org/10.4081/pb.2010.e13>
- Piedrahita, L. R. (2018). *The Effect of Flowering Synchrony and Floral Display on the Reproduction of a Gynodioecious Alpine Cushion Plant, Silene acaulis (Caryophyllaceae)*. Ph. D. Thesis. Appalachian State University.
- Pires, J. P., Marino, N. A., Silva, A. G., Rodrigues, P. J., & Freitas, L. (2018). Tree community phenodynamics and its relationship with climatic conditions in a lowland tropical rainforest. *Forests*, 9(3), 114. <https://doi.org/10.3390/f9030114>

- Polatto, L. P., & Junior, V. V. A. (2022). Foraging *Oxaea flavescens* bees as a function of the dynamics of abiotic factors and food resource availability from *Styrax camporum* flowers. *Acta Scientiarum. Biological Sciences*, 44. <https://doi.org/10.4025/actascibiolsci.v44i1.58568>
- Ponce, M., Gómez, F., Ojeda, S., Rodríguez-Gómez, G. B., Orellana, J. I., & Fontúrbel, F. E. (2024). The relative importance of local versus regional habitat structure variation on the abundance of two generalist mutualists along a forest disturbance gradient. *Global Ecology and Conservation*, 54, e03160. <https://doi.org/10.1016/j.gecco.2024.e03160>
- Pontes, C. A. D. S., Machado, I. C., & Domingos-Melo, A. (2024). Floral morphology and pollen placement strategies of bat-pollinated flowers: a comparative analysis within a guild of chiropterophilous plants in a neotropical dry forest. *Revista Chilena de Historia Natural*, 97(1), 11. <https://doi.org/10.1186/s40693-024-00133-9>
- Potts, S. G., Ngo, H. T., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J., & Vanbergen, A. (2016). The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production.
- Prance, G. T. (1980). A note on the probable pollination of *Combretum lanceolatum* by Cebus monkeys. *Biotropica*, 12(3), 239.
- Prasad, S. N., & Hegde, M. (1986). Phenology and seasonality in the tropical deciduous forest of Bandipur, South India. *Proceedings: Plant Sciences*, 96, 121-133. <https://doi.org/10.1007/BF03053328>
- Primack, R. B. (1980). Variation in the phenology of natural populations of montane shrubs in New Zealand. *The Journal of Ecology*, 849-862. <https://doi.org/10.2307/2259460>
- Proctor, M., Yeo P. and Lack, A. 1996. The natural history of pollination. Harper Collins, London.
- Putz, F. E. (1979). Aseasonality in Malaysian tree physiology. *Malaysian Forester*, 42, 1-24.
- Qian, D., Wang, M., Niu, Y., Yang, Y., & Xiang, Y. (2025). Sexual reproduction in plants under high temperature and drought stress. *Cell Reports*, 44(3). <https://doi.org/10.1016/j.celrep.2025.115390>
- Qu, R., Li, X., Luo, Y., Dong, M., Xu, H., Chen, X., & Dafni, A. (2007). Wind-dragged corolla enhances self-pollination: a new mechanism of delayed self-pollination. *Annals of Botany*, 100(6), 1155-1164. <https://doi.org/10.1093/aob/mcm209>
- Quesada, M., Rosas, F., Aguilar, R., Ashworth, L., Rosas-Guerrero, V. M., Sayago, R., Lobo, J. A., Herrerías-Diego, Y., & Sánchez-Montoya, G. (2011). Human Impacts on Pollination, Reproduction, and Breeding Systems in Tropical Forest Plants. In: Dirzo, R., Young, H. S., Mooney, H. A., Ceballos, G. (eds) Seasonally

- Dry Tropical Forests. Island Press, Washington, DC.
https://doi.org/10.5822/978-1-61091-021-7_11
- Rafferty, N. E., & Cosma, C. T. (2024). Sustainable nature-based solutions require establishment and maintenance of keystone plant-pollinator interactions. *Journal of Ecology*, 112(11), 2432-2441. <https://doi.org/10.1111/1365-2745.14353>
- Rahimi, E., & Jung, C. (2025). Trends in Pollination Scientists' Research: A Comprehensive Analysis in Citations and Research Topics. *Ecology and Evolution*, 15(5), e71215. <https://doi.org/10.1002/ece3.71215>
- Raina, R., Behera, M. C., Chand, R., & Sharma, Y. (2003). Reproductive biology of *Gentiana kurroo* Royle. *Current Science*, 667-670.
<http://www.jstor.org/stable/24109109>
- Raiol, R. L., Gastauer, M., Campbell, A. J., Borges, R. C., Awade, M., & Giannini, T. C. (2021). Specialist bee species are larger and less phylogenetically distinct than generalists in tropical plant–bee interaction networks. *Frontiers in Ecology and Evolution*, 9, 699649. <https://doi.org/10.3389/fevo.2021.699649>
- Rajkumar, K., Keshavanarayan, P., & Sivaram, V. (2015). Pollination biology and breeding system of *Eugenia discifera* Gamble-an endangered species of Western ghats, India. *International Journal of Science and Nature*, 6, 1-11.
- Raju, A. S. (2019). Styler polymorphisms in flowering plants: an overview. *Asymmetry in Plants*, 301-317.
- Raju, A. S., & Rao, S. P. (2002). Pollination ecology and fruiting behaviour in *Acacia sinuata* (Lour.) Merr.(Mimosaceae), a valuable non-timber forest plant species. *Current Science*, 82(12), 1466-1471.
- Raju, A. S., Ramana, K. V., & Jonathan, K. H. (2009). Anemophily, anemochory, seed predation and seedling ecology of *Shorea tumbuggaia* Roxb.(Dipterocarpaceae), an endemic and globally endangered, red-listed semi-evergreen tree species. *Current Science*, 96(6), 827-833.
- Raju, C., Pazhanivelan, S., Perianadar, I. V., Kaliaperumal, R., Sathyamoorthy, N. K., & Sendhilvel, V. (2024). Climate Change as an Existential Threat to Tropical Fruit Crop Production - A Review. *Agriculture*, 14(11).
<https://doi.org/10.3390/agriculture14112018>
- Ramasubbu, R., & Irudhyaraj, D. F. (2016). Reproductive biology of *Elaeocarpus blascoi* Weibel, an endemic and endangered tree species of Palni Hills, Western Ghats, India. *Current Science*, 110(2), 234-240.
- Ramasubbu, R., Sreekala, A. K., Pandurangan, A. G., & Kulloli, S. K. (2011). Reproductive ecology of *Impatiens platyadena* Fischer, a critically endangered balsam of Western Ghats. *Current Science*, 100(10), 1550-1554.
- Ramírez, F., & Kallarackal, J. (2018). Climate change, tree pollination and conservation in the tropics: a research agenda beyond IPBES. *Wiley*

- Interdisciplinary Reviews: Climate Change*, 9(1), e502.
<https://doi.org/10.1002/wcc.502>
- Rands, S. A., & Whitney, H. M. (2008). Floral temperature and optimal foraging: is heat a feasible floral reward for pollinators?. *PloS One*, 3(4), e2007.
<https://doi.org/10.1371/journal.pone.0002007>
- Ranpal, S., von Bargaen, S., Gilles, S., Luschkova, D., Landgraf, M., Traidl-Hoffmann, C., Büttner, C., Damialis, A., & Jochner-Oette, S. (2023). Pollen production of downy birch (*Betula pubescens* Ehrh.) along an altitudinal gradient in the European Alps. *International Journal of Biometeorology*, 67(6), 1125-1139.
<https://doi.org/10.1007/s00484-023-02483-7>
- Rashid, K., Rashid, S., Ganie, A., Nawchoo, I., & Khuroo, A. (2023). Reproductive biology of *Trillium govanianum*, an endangered plant species endemic to the Himalaya: implications for conservation. *Botany Letters*, 170, 565 - 580.
<https://doi.org/10.1080/23818107.2023.2176355>
- Rasmussen, N. L., & Yang, L. H. (2023). Timing of a plant–herbivore interaction alters plant growth and reproduction. *Ecology*, 104(1), e3854.
<https://doi.org/10.1002/ecy.3854>
- Rathod, V., Behera, T. K., Munshi, A. D., Durgesh, K., Jat, G. S., Krishnan, B. G., & Sharma, N. (2018). Pollen viability and in vitro pollen germination studies in *Momordica* species and their intra and interspecific hybrids. *International Journal of Chemical Studies*, 6(6), 32-40.
- Ratto, F., Simmons, B. I., Spake, R., Zamora-Gutierrez, V., MacDonald, M. A., Merriman, J. C., Tremlett, C. J., Poppy, G. M., Peh, K. S. H., & 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. <https://doi.org/10.1002/fee.1763>
- Rech, A. R., Jorge, L. R., Ollerton, J., & Sazima, M. (2018). Pollinator availability, mating system and variation in flower morphology in a tropical savanna tree. *Acta Botanica Brasilica*, 32, 462-472. <https://doi.org/10.1590/0102-33062018abb0220>
- Reddi, C. S., Reddi, N. S., & Janaki, B. A. (1988). Circadian patterns of pollen release in some species of Poaceae. *Review of Palaeobotany and Palynology*, 54(1-2), 11-42. [https://doi.org/10.1016/0034-6667\(88\)90003-6](https://doi.org/10.1016/0034-6667(88)90003-6)
- Renjumol, R., & Radhamany, P. M. (2017). Reproductive biology of *Amherstia nobilis* Wall. (Fabaceae). *International Journal of Plant Reproductive Biology*, 9(1), 73-76.
- Renner, S. S., & Ricklefs, R. E. (1995). Dioecy and its correlates in the flowering plants. *American Journal of Botany*, 82(5), 596-606.
<https://doi.org/10.1002/j.1537-2197.1995.tb11504.x>
- Reverté, S., Retana, J., Gómez, J. M., & Bosch, J. (2016). Pollinators show flower colour preferences but flowers with similar colours do not attract similar

- pollinators. *Annals of Botany*, 118(2), 249-257.
<https://doi.org/10.1093/aob/mcw103>
- Richards, A. J. (1997). *Plant Breeding Systems*. Chapman & Hall, London.
- Rodger, Y. S., Dillon, R., Monro, K., Pavlova, A., Coates, D. J., Byrne, M., & Sunnucks, P. (2024). Benefits of outcrossing and their implications for genetic management of an endangered species with mixed-mating system. *Restoration Ecology*, 32(1), e14057. <https://doi.org/10.1111/rec.14057>
- Rodrigues, D. M., Turchetto, C., Lima, J. S., & Freitas, L. B. (2019). Diverse yet endangered: pollen dispersal and mating system reveal inbreeding in a narrow endemic plant. *Plant Ecology & Diversity*, 12(2), 169-180.
<https://doi.org/10.1080/17550874.2019.1610914>
- Rodriguez-Riano, T., & Dafni, A. (2000). A new procedure to assess pollen viability. *Sexual Plant Reproduction*, 12, 241-244.
<https://doi.org/10.1007/s004970050008>
- Roguz, K., Pstrokoński, P., Ryniewicz, J., Chmur, M., Bajguz, A., & Sapir, Y. (2025). Environment or Pollinators? Factors Shaping Breeding System and Spatial Variation in Nectar Properties and Pollination System in a Desert Species *Fritillaria persica* L. (Liliaceae). *Ecology and Evolution*, 15(4), e71265.
<https://doi.org/10.1002/ece3.71265>
- Rojas-Nossa, S. V., & Calviño-Cancela, M. (2020). The invasive hornet *Vespa velutina* affects pollination of a wild plant through changes in abundance and behaviour of floral visitors. *Biological Invasions*, 22(8), 2609-2618.
<https://doi.org/10.1007/s10530-020-02275-9>
- Rueda-Urbe, C., Chautá, A., Woodman, T. L., Lasso, E., Pelayo, R. C., Manrique-Garzón, L. M., Muñoz, M. C., Allgayer, R., Ashman, T., Bocedi, G., Burslem, D. F. R. P., Camargo-Martínez, P. A., Echeverry-Galvis, M. A., Gonzalez-Arango, C., Gubry-Rangin, C., Lancaster, L. T., Layton, K. K. S., Manfredini, F., Martel, C., Montti, L., Papadopoulos, A. S. T., Raguso, R. A., Ready, J., Rico-Guevara, A., Rocabado, C., & Travis, J. M. (2025). Pollination ecology in the tropical Andes: moving towards a cross-scale approach. *Biological Reviews*, 1-35. <https://doi.org/10.1111/brv.70049>
- Russ, L. (1999). Regeneration and flying foxes. In: *Rainforest Remnants: A Decade of Growth*. Horton, S. (ed.). NSW National Parks and Wildlife Services, Hurstville, pp.188-206.
- Rymer, P. D., Whelan, R. J., Ayre, D. J., Weston, P. H., & Russell, K. G. (2005). Reproductive success and pollinator effectiveness differ in common and rare *Persoonia* species (Proteaceae). *Biological Conservation*, 123(4), 521-532.
<https://doi.org/10.1016/j.biocon.2005.01.002>
- Sabu, V. U. (2024). Seasonal pollination dynamics of *Cymbidium aloifolium* by *Apis cerana* Indica Honey Bees in the Western Ghats, Wayanad. *International Journal for Multidisciplinary Research*, 6(4), 1-4.

- Sagili, R. R., Chakrabarti, P., Melathopoulos, A., Delaplane, K. S., Dag, A., Danka, R. G., ... & Steinhauer, N. (2025). Standard methods for pollination research with *Apis mellifera* 2.0. *Journal of Apicultural Research*, 64(2), 612-646. <https://doi.org/10.1080/00218839.2024.2369284>
- Saha, M., & Datta, B. K. (2017). Observations on the reproductive biology of *Solanum torvum* Swartz (Solanaceae): an important medicinal plant in North-east India. *International Journal of Plant Reproductive Biology*, 9(1), 25-27. <https://doi.org/10.14787/ijprb.2017.9.1.25-27>
- Saha, R., Ghosh, P. K., Mishra, V. K., Majumdar, B., & Tomar, J. M. S. (2010). Can agroforestry be a resource conservation tool to maintain soil health in the fragile ecosystem of north-east India?. *Outlook on Agriculture*, 39(3), 191-196. <https://doi.org/10.5367/oa.2010.0>
- Sahu, B. K., Parganiha, A., & Pati, A. K. (2019). Spatiotemporal variability in activity patterns of urban street cattle as function of environmental factors. *Chronobiology International*, 36(10), 1362-1372. <https://doi.org/10.1080/07420528.2019.1644345>
- Saini, R., & Sihag, R. C. (2020). Flowering biology and phenology of Aonla (*Embllica officinalis* Gaertn.) in the semi-arid environment of north-West India. *International Journal of Agricultural Research*, 15, 1-8. <https://doi.org/10.3923/ijar.2020.1.8>
- Saitluanga, B. L., Lalchhandama, G., & Rinawma, P. (2021). Analysis of Climate Variability and Agricultural Productivity in Mizoram, Northeast India. *Acta Geographica Debrecina Landscape & Environment Series*, 15(2), 53-64. <https://doi.org/10.21120/LE/15/2/5>
- Sakai, S. (2001). Phenological diversity in tropical forests. *Population Ecology*, 43(1), 77-86. <https://doi.org/10.1007/PL00012018>
- Sakar EH, Yamani ME, Boussakouran A, Rharrabti Y (2019) Codification and description of almond (*Prunus dulcis*) vegetative and reproductive phenology according to the extended BBCH scale. *Scientia Horticulturae*, 247:224-234. <https://doi.org/10.1016/j.scienta.2018.12.024>
- Sampaio, D. S., Mendes-Rodrigues, C., Engel, T. B., Rezende, T. M., Bittencourt-Jr, N. S., & Oliveira, P. E. (2016). Pollination biology and breeding system of syntopic *Adenocalymma nodosum* and *A. peregrinum* (Bignoniaceae, Bignoniaceae) in the Brazilian savanna. *Flora*, 223, 19-29. <https://doi.org/10.1016/j.flora.2016.04.009>
- Samy, K. K., & Ramasubbu, R. (2022). Floral traits and phenology drive pollinators diversity and pollinators visits in selected endemic *Elaeocarpus* spp. of the Western Ghats. *Acta Ecologica Sinica*, 42(4), 296-311. <https://doi.org/10.1016/j.chnaes.2021.12.003>
- Sanchez, M., Abreu, A. C., Tristán, A. I., Velásquez, Y., Fernández, I., & Cuevas, J. (2024). Floral attractants and rewards to pollinators in *Mangifera indica* L.

<https://doi.org/10.1016/j.scienta.2024.113180>

- Sasaki, N., Zhang, L., Meadows, J., Seo, J. W., & Boehmer, H. J. (2024). Dynamics of Asia's and Australasia's forests in a changing world. *Frontiers in Forests and Global Change*, 7, 1474882. <https://doi.org/10.3389/ffgc.2024.1474882>
- Sathischandra, M. K. D. P. M. (2024). A Review on the Utilization of Herbarium Data in Phenological Research Addressing Climate Change Implications. In *Proceedings of International Forestry and Environment Symposium (Vol. 28)*. <https://doi.org/10.31357/fesympo.v28.7122>
- Sati, V. P., & Vangchhia, L. (2016). Altitudinal Zonation of Floral Biodiversity and Its Conservation Pattern in Mizoram, North-East India. In *Environmental Geography of South Asia: Contributions Toward a Future Earth Initiative* (pp. 177-187). Springer Japan. https://doi.org/10.1007/978-4-431-55741-8_11
- Satish, D., & Ravikumar, R. L. (2010). Standardization of *in vitro* pollen germination media in selected varieties of cotton and tomato. *Karnataka Journal of Agricultural Science*, 23, 317-319.
- Scaven, V. L., & Rafferty, N. E. (2013). Physiological effects of climate warming on flowering plants and insect pollinators and potential consequences for their interactions. *Current Zoology*, 59(3), 418-426. <https://doi.org/10.1093/czoolo/59.3.418>
- Ščevková, J., Dušička, J., Zahradníková, E., Sepšiová, R., Kováč, J., & Vašková, Z. (2023). Impact of meteorological parameters and air pollutants on airborne concentration of Betula pollen and Bet v 1 allergen. *Environmental Science and Pollution Research*, 30(42), 95438-95448. <https://doi.org/10.1007/s11356-023-29061-z>
- Schlicht, M., Ludwig-Müller, J., Burbach, C., Volkmann, D., & Baluska, F. (2013). Indole-3-butyric acid induces lateral root formation via peroxisome-derived indole-3-acetic acid and nitric oxide. *New Phytologist*, 200(2), 473-482. <https://doi.org/10.1111/nph.12377>
- Schoen, D. J., Johnson, M. T., & Wright, S. I. (2019). The ecology, evolution, and genetics of plant reproductive systems. *The New Phytologist*, 224(3), 999-1004.
- Seijo, J. G., & Solis Neffa, V. G. (2004). The cytological origin of the polyads and their significance in the reproductive biology of *Mimosa bimucronata*. *Botanical Journal of the Linnean Society*, 144(3), 343-349. <https://doi.org/10.1111/j.1095-8339.2003.00253.x>
- Seitz, J., Reimann, T. M., Fritz, C., Schröder, C., Knab, J., Weber, W., & Stadler, R. (2023). How pollen tubes fight for food: the impact of sucrose carriers and invertases of *Arabidopsis thaliana* on pollen development and pollen tube growth. *Frontiers in Plant Science*, 14, 1063765. <https://doi.org/10.3389/fpls.2023.1063765>

- Semerdjieva, I., Yankova-Tsvetkova, E., Zheljazkov, V. D., Koleva-Valkova, L. H., & Nikolova, R. (2023). Reproductive capacity and scanning electron microscopy (SEM) analyses of the micromorphological surfaces of three endemic *Satureja* species from Bulgaria. *Plants*, 12(13), 2436. <https://doi.org/10.3390/plants12132436>
- Seo, H. J., Park, Y., Choi, E. D., Lee, B., Hong, S. S., Sawant, S. S., Yu, S., & Lee, C. G. (2025). Effects of drone-assisted artificial pollination on fruit set and characteristics in Asian pear. *Journal of Horticultural Science and Biotechnology*, 1-10. <https://doi.org/10.1080/14620316.2025.2529849>
- Shaina, T. J., & Beevy, S. S. (2015). Reproductive biology of *Coccinia grandis* (L.) Voigt, a dioecious vegetatively propagated cucurbit: evidence for facultative apomixis. *International Journal of Plant Reproductive Biology*, 7(1), 67-77.
- Sharma, B., Hajam, Y. A., & Kumar, R. (2021). Prototype development for composite mud house for *Apis cerana* using local ingredients to conserve indigenous beekeeping. *Journal of Entomology and Zoology Studies*, 9(4), 214-217.
- Sharma, L. K., & Naik, R. (2024). Saline Wetland Ecosystems. In *Conservation of Saline Wetland Ecosystems: An Initiative towards UN Decade of Ecological Restoration* (pp. 33-75). Singapore: Springer Nature Singapore.
- Sharma, M. V., Shaanker, R. U., Vasudeva, R., & Shivanna, K. R. (2010). Functional dioecy in *Nothapodytes nimmoniana*, a distylous species in the Western Ghats. *Current Science*, 1444-1449.
- Sharma, P., Roy, M., & Roy, B. (2022). A review on influence of floral biology, pollination efficiency and conservation strategies of endangered medicinal plant, *Rauvolfia serpentina* (L.) Benth. ex Kurz. *Annals of Phytomedicine*, 11(1), 86-98. <http://dx.doi.org/10.54085/ap.2022.11.1.9>
- Shine, R., & Brown, G. P. (2008). Adapting to the unpredictable: reproductive biology of vertebrates in the Australian wet-dry tropics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1490), 363-373. <https://doi.org/10.1098/rstb.2007.2144>
- Shivanna, K. R. & Rangaswamy, N. S. (1992). *Pollen Biology – A Laboratory Manual*, Narosa Publishing House, New Delhi.
- Shivanna, K. R. (2003). *Pollen biology and biotechnology*. CRC Press. <https://doi.org/10.1201/9780429187704>
- Shivanna, K. R. (2009). Pollination biology, breeding system and reproductive success of *Adhatoda vasica*, an important medicinal plant. *Current science*, 96(3), 408-412.
- Shivanna, K. R. (2023). Role of Secondary Metabolites in Pollination. In: Mérillon, JM., Ramawat, K.G. (eds) *Plant Specialized Metabolites*. Reference Series in Phytochemistry. Springer, Cham. https://doi.org/10.1007/978-3-031-30037-0_21-1

- Shivanna, K. R., & Johri, B. M. (1989). The angiosperm pollen structure and function. Wiley Eastern Ltd. New Delhi.
- Shivanna, K. R., & Sanjappa, M. (2021). Conservation of endemic and threatened flowering plants: challenges and priorities for India. *Journal of Indian Botanical Society*, 101, 269-290.
- Shivanna, K. R., & Tandon, R. (2014). Reproductive ecology of flowering plants: a manual (pp. 107-123). New Delhi: Springer India.
- Shivanna, K. R., Linskens, H. F., & Cresti, M. (1991). Pollen viability and pollen vigor. Theoretical and applied genetics, 81, 38-42. <https://doi.org/10.1007/BF00226109>
- Shivanna, K. R., Saxena, N. P., & Seetharama, N. (1997). An improvised medium for in vitro pollen germination and pollen tube growth of chickpea. *International Chickpea and Pigeon pea*, Newsletter, 4, 28-29.
- Shrestha, M., Tai, K. C., Dyer, A. G., Garcia, J. E., Yang, E. C., Jentsch, A., & Wang, C. N. (2024). Flower colour and size-signals vary with altitude and resulting climate on the tropical-subtropical islands of Taiwan. *Frontiers in Plant Science*, 15, 1304849. <https://doi.org/10.3389/fpls.2024.1304849>
- Silva, A. G., Freitas, L., & Pires, J. P. A. (2014). A Fournier Index upgrade as a new approach for quantitative phenological studies in plant communities. *Tropical Ecology*, 55(1), 137-142.
- Silva, J. L. S., Barros, M. F., Rito, K. F., Cruz-Neto, O., Tabarelli, M., Leal, I. R., Ulysses, P. A., Rainer, W., & Lopes, A. V. (2024). Use of woody species in the Caatinga dry forest may lead to higher vulnerability to extirpation: An assessment based on ethnobiological, reproductive and conservation criteria. *Flora*, 317, 152568. <https://doi.org/10.1016/j.flora.2024.152568>
- Simla, P., Chaianunporn, T., Sankamethawee, W., Hughes, A. C., & Sritongchuay, T. (2022). Effect of landscape composition and invasive plants on pollination networks of smallholder orchards in northeastern Thailand. *Plants*, 11(15), 1976. <https://doi.org/10.3390/plants11151976>
- 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. <https://doi.org/10.1016/j.jnc.2024.126742>
- Singh, J. S., & Singh, V. K. (1992). Phenology of seasonally dry tropical forest. *Current science*, 63(11), 684-689.
- Singh, K., & Kushwaha, C. (2006). Diversity of flowering and fruiting phenology of trees in a tropical deciduous forest in India. *Annals of Botany*, 97 2, 265-76 . <https://doi.org/10.1093/AOB/MCJ028>
- Singh, R., Sah, M., & Upadhayay, D. (2016). Rudraksh-Documentation of Geographical Distribution, Reason for Decline, Measures to Enhance

- Propagation. Indian National Trust for Art and Cultural Heritage (INTACH) 71, Lodhi Estate, New Delhi.
- Skjøth, C. A., Kurganskiy, A., Grundström, M., Werner, M., & Adams-Groom, B. (2021). Air pollution affecting pollen concentrations through radiative feedback in the atmosphere. *Atmosphere*, 12(11), 1376. <https://doi.org/10.3390/atmos12111376>
- Smitha, G. R., & Thondaiman, V. (2016). Reproductive biology and breeding system of *Saraca asoca* (Roxb.) De Wilde: a vulnerable medicinal plant. Springerplus, 5(1), 2025. <https://doi.org/10.1186/s40064-016-3709-9>
- Smits, N. A. C. (2010). Restoration of nutrient-poor grasslands in Southern Limburg Vegetation development and the role of soil processes. Wageningen University and Research.
- Soares, E. L., Landi, L. A. D. C., Souza, C. N. D., & Gasparino, E. C. (2022). Polyads types of the mimosoid clade (Caesalpinioideae, Fabaceae): size and pollen numbers variations. *Grana*, 61(1), 45-66. <https://doi.org/10.1080/00173134.2021.1990397>
- Sodhi, N. S., Brook, B. W., & Bradshaw, C. J. (2013). Tropical conservation biology. John Wiley & Sons.
- Sofiev, M., Buters, J., Tummon, F., Fatahi, Y., Sozinova, O., Adams-Groom, B., Bergmann, K. C., Dahl, A., Gehrig, R., Gilge, S., Seliger, A. K., Kouznetsov, R., Lieberherr, G., O'Connor, D., Oteros, J., Palamarchuk, J., Ribeiro, H., Werchan, B., Werchan, M., & Clot, B. (2023). Designing an automatic pollen monitoring network for direct usage of observations to reconstruct the concentration fields. *Science of the Total Environment*, 900, 165800. <https://doi.org/10.1016/j.scitotenv.2023.165800>
- Solis-Montero, L., Landaverde-González, P., Zamora-Gutierrez, V., & He, X. (2023). The forgotten pollinators: the importance and conservation of wild pollinators. *Frontiers in Sustainable Food Systems*, 7, 1323557. <https://doi.org/10.3389/fsufs.2023.1323557>
- Souza EH, Carmello-Guerreiro SM, Souza FVD, Rossi ML, Martinelli AP (2016) Stigma structure and receptivity in Bromeliaceae. *Scientia Horticulturae*. 203:118-125. <https://doi.org/10.1016/j.scienta.2016.03.022>
- Souza, C. S., Maruyama, P. K., Aoki, C., Sigrist, M. R., Raizer, J., Gross, C. L., & de Araujo, A. C. (2018). Temporal variation in plant–pollinator networks from seasonal tropical environments: higher specialization when resources are scarce. *Journal of Ecology*, 106(6), 2409-2420. <https://doi.org/10.1111/1365-2745.12978>
- Souza, C. V., Nepi, M., Machado, S. R., & Guimarães, E. (2017). Floral biology, nectar secretion pattern and fruit set of a threatened Bignoniaceae tree from Brazilian tropical forest. *Flora*, 227, 46-55. <https://doi.org/10.1016/j.flora.2016.12.007>

- Spira, T. P. (2001). Plant-pollinator interactions: a threatened mutualism with implications for the ecology and management of rare plants. *Natural Areas Journal*, 21, 78-88.
- Springate, D. A., & Kover, P. X. (2014). Plant responses to elevated temperatures: a field study on phenological sensitivity and fitness responses to simulated climate warming. *Global Change Biology*, 20(2), 456-465. <https://doi.org/10.1111/gcb.12430>
- Sreekala, A. K., Pandurangan, A. G., Ramasubbu, R., & Kulloli, S. K. (2008). Reproductive biology of *Impatiens coelotropis* Fisher, a critically endangered balsam from the Southern Western Ghats. *Current Science*, 95, 386-388.
- Ssali, F., & Sheil, D. (2023). Seasonality in the equatorial tropics: Flower, fruit, and leaf phenology of montane trees in the highlands of Southwest Uganda. *Biotropica*, 55(3), 680-698. <https://doi.org/10.1111/btp.13219>
- Statistical Handbook of Mizoram (2022), Directorate of Economics and Statistics, Mizoram: Aizawl.
- Steffan-Dewenter, I., & Tscharntke, T. (1999). Effects of habitat isolation on pollinator communities and seed set. *Oecologia*, 121, 432-440. <https://doi.org/10.1007/s004420050949>
- Steinecke, C., Gorman, C. E., Stift, M., & Dorken, M. E. (2022). Outcrossing rates in an experimentally admixed population of self-compatible and self-incompatible *Arabidopsis lyrata*. *Heredity*, 128(1), 56-62. <https://doi.org/10.1038/s41437-021-00489-8>
- Stokes, M., & Geitmann, A. (2025). Screening methods for thermotolerance in pollen. *Annals of Botany*, 135(1-2), 71-88. <https://doi.org/10.1093/aob/mcae067>
- 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. <https://doi.org/10.1002/j.1537-2197.1995.tb11591.x>
- Storrs, A., & Storrs, J. (1990). Trees and Shrubs of Nepal and the Himalayas. Pp. 102-106.
- Subha, V., & Richard, S. S. (2016). Floral structure and the fruit-set in *Psydrax dicoccos* Gaertn.(Rubiaceae) in relation to foraging behaviour of floral visitors. *International Journal of Plant Reproductive Biology*, 8(2), 173-185.
- Subramanya, S., & Radhamani, T. R. (1993). Pollination by birds and bats. *Current Science*, 65(3), 201-209.
- Sullivan, M. K., Fayolle, A., Bush, E., Ofosu-Bamfo, B., Vleminckx, J., Metz, M. R., & Queenborough, S. A. (2024). Cascading effects of climate change: new advances in drivers and shifts of tropical reproductive phenology. *Plant Ecology*, 225(3), 175-187. <https://doi.org/10.1007/s11258-023-01377-3>
- Sun, H. Q., Alexandersson, R., & Ge, S. (2010). Positive effects of flower abundance and synchronous flowering on pollination success, and pollinia dispersal in rewardless *Changnienia amoena* (Orchidaceae). *Biological Journal of the*

- Linnean Society*, 99(3), 477-488. <https://doi.org/10.1111/j.1095-8312.2009.01369.x>
- Surina, B., Balant, M., Glasnović, P., Gogala, A., Fišer, Ž., Satovic, Z., Liber, Z., Radosavljević, I., & Classen-Bockhoff, R. (2024). Lack of pollinators selects for increased selfing, restricted gene flow and resource allocation in the rare Mediterranean sage *Salvia brachyodon*. *Scientific Reports*, 14(1), 5017. <https://doi.org/10.1038/s41598-024-55344-7>
- Swami, S. (2018). Shifting cultivation: a tribal way of life in north east India and alternative approaches for increasing productivity. *Pharma Innovation Journal*, 7(3), 380-385.
- Tachiki, Y., Iwasa, Y., & Satake, A. (2010). Pollinator coupling can induce synchronized flowering in different plant species. *Journal of Theoretical Biology*, 267(2), 153-163. <https://doi.org/10.1016/j.jtbi.2010.08.023>
- Takkis, K., Tscheulin, T., & Petanidou, T. (2018). Differential effects of climate warming on the nectar secretion of early-and late-flowering Mediterranean plants. *Frontiers in Plant Science*, 9, 874. <https://doi.org/10.3389/fpls.2018.00874>
- Talavera, S., Bastida, F., Ortiz, P. L., & Arista, M. (2001). Pollinator attendance and reproductive success in *Cistus libanotis* L.(Cistaceae). *International Journal of Plant Sciences*, 162(2), 343-352. <https://doi.org/10.1086/319573>
- Tanaka, N., & Wada, M. (2022). Apple MADS genes are involved in parthenocarpy and floral organ formation. *The Horticulture Journal*, 91(2), 131-139. <https://doi.org/10.2503/hortj.UTD-R018>
- Tandon, R., Koul, M., & Shivanna, K. R. (2020). Reproductive Ecology of Flowering Plants: An Introduction. In: Tandon, R., Shivanna, K., Koul, M. (eds) *Reproductive Ecology of Flowering Plants: Patterns and Processes*. Springer, Singapore. https://doi.org/10.1007/978-981-15-4210-7_1
- Tandon, R., Shivanna, K. R., & Mohan Ram, H. Y. (2003). Reproductive biology of *Butea monosperma* (Fabaceae). *Annals of Botany*, 92(5), 715-723. <https://doi.org/10.1093/aob/mcg193>
- Teixido, A. L., Fuzessy, L. F., Souza, C. S., Gomes, I. N., Kaminski, L. A., Oliveira, P. C., & Maruyama, P. K. (2022). Anthropogenic impacts on plant-animal mutualisms: A global synthesis for pollination and seed dispersal. *Biological Conservation*, 266, 109461. <https://doi.org/10.1016/j.biocon.2022.109461>
- Tel-Zur, N. (2023). Preventing self-fertilization: Insights from *Ziziphus* species. *Frontiers in Plant Science*, 14, 1226502. <https://doi.org/10.3389/fpls.2023.1226502>
- Teng, Y., Villalobos, S., Vamosi, J. C., Wang, X. F., & Gong, Y. B. (2024). Diurnal versus nocturnal pollination in a subalpine wetland: From network structure to plant reproduction. *Global Ecology and Conservation*, 49, e02798. <https://doi.org/10.1016/j.gecco.2024.e02798>

- Thomann, M., Imbert, E., Devaux, C., & Cheptou, P. O. (2013). Flowering plants under global pollinator decline. *Trends in Plant Science*, 18(7), 353-359. <https://doi.org/10.1016/j.tplants.2013.04.002>
- Thomas, E., Jalonen, R., Loo, J., Boshier, D., Gallo, L., Cavers, S., Bordács, S., Smith, P., & Bozzano, M. (2014). Genetic considerations in ecosystem restoration using native tree species. *Forest Ecology and Management*, 333, 66-75. <https://doi.org/10.1016/j.foreco.2014.07.015>
- Thorat, B., Kunkerkar, R., Kadam, S., Bhawe, S., & Devmore, J. (2020). Study of anther dehiscence, pollen viability and stigma receptivity in rice (*Oryza sativa* L.). *International Journal of Chemical Studies*, 8(3), 2677-2680. <https://doi.org/10.22271/chemi.2020.v8.i3am.9616>
- Tiedge, K., & Lohaus, G. (2018). Nectar sugar modulation and cell wall invertases in the nectaries of day-and night-flowering *Nicotiana*. *Frontiers in Plant Science*, 9, 622. <https://doi.org/10.3389/fpls.2018.00622>
- 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. <https://doi.org/10.1111/brv.12745>
- Tiwari, H., Sekar, K. C., Pandey, A., Tiwari, A., Mehta, P., Kanwal, K. S., & Arya, D. (2024). Diversity, distribution and need of urgent conservation of endemic plants in Himalaya. *Biodiversity and Conservation*, 1-19. <https://doi.org/10.1007/s10531-024-02815-y>
- Torre, A. R. D. L., Roberts, D. R., & Aitken, S. N. (2014). Genome-wide admixture and ecological niche modelling reveal the maintenance of species boundaries despite long history of interspecific gene flow. *Molecular Ecology*, 23(8), 2046-2059. <https://doi.org/10.1111/mec.12710>
- Trueman, S. J., Nichols, J., Burwell, C. J., & Kämper, W. (2025). Strategic selection of polliniser trees can improve fruit quality of lychee, a crop that exhibits mixed-mating. *Basic and Applied Ecology*, 83, 80-87. <https://doi.org/10.1016/j.baaec.2025.01.010>
- Trunschke, J., Junker, R. R., Kudo, G., Alexander, J. M., Richman, S. K., & Till-Bottraud, I. (2024). Effects of climate change on plant-pollinator interactions and its multitrophic consequences. *Alpine Botany*, 1-7. <https://doi.org/10.1007/s00035-024-00316-w>
- Tsuji, K., Kobayashi, K., Hasegawa, E., & Yoshimura, J. (2020). Dimorphic flowers modify the visitation order of pollinators from male to female flowers. *Scientific Reports*, 10(1), 9965. <https://doi.org/10.1038/s41598-020-66525-5>
- Tsuzuki, Y., & Ohara, M. (2022). Temporal skewness of pollination success in the spring ephemeral *Trillium camschatcense*. *The Science of Nature*, 109(4), 35. <https://doi.org/10.1007/s00114-022-01807-8>
- Tuinstra, M. R., & Wedel, J. (2000). Estimation of pollen viability in grain sorghum. *Crop science*, 40(4), 968-970. <https://doi.org/10.2135/cropsci2000.404968x>

- Tun, W., Yoon, J., Jeon, J. S., & An, G. (2021). Influence of climate change on flowering time. *Journal of Plant Biology*, 64(3), 193-203. <https://doi.org/10.1007/s12374-021-09300-x>
- Tylianakis, J. M. (2013). The global plight of pollinators. *Science*, 339(6127), 1532-1533. <https://doi.org/10.1126/science.123546>
- Ueda, Y., & Tomita, H. (1989). Morphometric analysis of pollen exine patterns in roses. *Journal of the Japanese Society for Horticultural Science*, 58(1), 211-220. <https://doi.org/10.2503/jjshs.58.211>
- Usha, V. K. M., & Devi, M. S. (2020). Effect of environmental factors on the foraging activities of major bee pollinators. *Journal of Entomology and Zoology Studies*, 8(2), 450-454.
- van Diggelen, R., Grootjans, A. P., & Harris, J. A. (2001). Ecological restoration: State of the art or state of the science?. *Restoration Ecology*, 9(2).
- van Tussenbroek, B. I., Wong, J. R., & Márquez-Guzman, J. (2008). Synchronized anthesis and predation on pollen in the marine angiosperm *Thalassia testudinum* (Hydrocharitaceae). *Marine Ecology Progress Series*, 354, 119-124. <https://doi.org/10.3354/meps07212>
- Vanlalruati, C., Zarzoliana & Thlanga, V. L. S. (2024). Mizoram forest after India's independence: bamboo, wild-life and land use. *International Journal of Advanced Research*, 1041-1047. <https://dx.doi.org/10.21474/IJAR01/19147>
- Varga, S., Nuortila, C., & Kytöviita, M. M. (2013). Nectar sugar production across floral phases in the gynodioecious protandrous plant *Geranium sylvaticum*. *PLoS One*, 8(4), e62575. <https://doi.org/10.1371/journal.pone.0062575>
- Veereshkumar, Kaushik, S. K., Rajarajan, K., Kumaranag, K. M., Uthappa, A. R., Sridhar, K. B., Alam, B., & Handa, A. K. (2021). Pollination biology of *Pongamia pinnata* (L.) Pierre: a potential biodiesel plant. *Genetic Resources and Crop Evolution*, 68(1), 59-67. <https://doi.org/10.1007/s10722-020-01010-6>
- Veni, S. K., & Richard, P. S. S. (2018). Floral morpho-anatomy and the pollination mechanism of *Atalantia monophylla* DC. *International Journal of Plant Reproductive Biology*, 10(1), 90-95.
- Vera, G. A. B., & Pérez, F. (2024). Floral nectar (FN): drivers of variability, causes, and consequences. *Brazilian Journal of Botany*, 1-11. <https://doi.org/10.1007/s40415-024-01009-8>
- Verma, R. (2024). Sustainable Growth Through Watershed Development: A Case Study of Mizoram. Available at SSRN 4767735. <http://dx.doi.org/10.2139/ssrn.4767735>
- Vinson, C. C., Mangaravite, E., Sebbenn, A. M., & Lander, T. A. (2018). Using molecular markers to investigate genetic diversity, mating system and gene flow of Neotropical trees. *Brazilian Journal of Botany*, 41, 481-496. <https://doi.org/10.1007/s40415-018-0472-x>

- Viswanathan, M. B., Rajasekar, C., & Kumar, P. S. (2019). Reproductive biology and pollinators of a steno-endemic and critically endangered tree, *Monoon tirunelveliense* (Annonaceae), from Kalakkad-Mundanthurai Tiger Reserve (KMTR), India. *Indian Journal of Experimental Biology*, 57(7).
- Vitasse, Y., Signarbieux, C., & Fu, Y. H. (2018). Global warming leads to more uniform spring phenology across elevations. *Proceedings of the National Academy of Sciences*, 115(5), 1004-1008. <https://doi.org/10.1073/pnas.1717342115>
- Vizintin, L., & Bohanec, B. (2004). In vitro manipulation of cucumber (*Cucumis sativus* L.) pollen and microspores: isolation procedures, viability tests, germination, maturation. *Acta Biologica Cracoviensia Series Botanica*, 46, 177-183.
- Voyiatzis, D. G., & Paraskevopoulou-Paroussi, G. (2000, July). The effect of photoperiod and gibberellic acid on strawberry pollen germination and stamen growth. In IV International Strawberry Symposium 567 (pp. 257-260). <https://doi.org/10.17660/ActaHortic.2002.567.52>
- Walker, J. W. (1971). Pollen morphology, phytogeography, and phylogeny of the Annonaceae. Contributions from the Gray Herbarium of Harvard University, (202), 1-130.
- Wandrag, E. M., Gibson, M. R., & Rodger, J. G. (2023). Reproductive Mutualisms of Australian Acacia Species. In *Wattles: Australian Acacia Species Around the World* (pp. 265-283). <https://doi.org/10.1079/9781800622197.0017>
- Wang, M., Wang, Z., Yang, Y., Zhao, X., Zhou, H., Zhou, S., Yin, X., Ren, Y., Dong, H., Zhang, L., Ma, Z., & Zhang, C. (2024). Influences of elevational gradient on flower size and number of *Gentiana lawrencei* var. *farreri*. *Ecology and Evolution*, 14(5), e11393. <https://doi.org/10.1002/ece3.11393>
- Wang, S. P., Meng, F. D., Duan, J. C., Wang, Y. F., Cui, X. Y., Piao, S. L., Niu, H.S., Xu, G. P., Luo, C. Y., Zhang, Z. H., Zhu, X.X., Shen, M. G., Li, Y. N., Du, M. Y., Tang, Y. H., Zhao, X. Q., Ciais, P., Kimball, B., Peñuelas, J., Janssens, I. A., Cui, S. J., Zhao, L., & Zhang, F. W. (2014). Asymmetric sensitivity of first flowering date to warming and cooling in alpine plants. *Ecology*, 95(12), 3387-3398. <https://doi.org/10.1890/13-2235.1>
- Wang, X., Morin, X., Zhang, J., Chen, G., Mao, L., Chen, Y., Song, Z., Du, Y., & Ma, K. (2023). Geographical patterns and determinants in plant reproductive phenology duration. *Frontiers in Plant Science*, 14, 1199316. <https://doi.org/10.3389/fpls.2023.1199316>
- Wang, X., Zeng, T., Wu, M., & Zhang, D. (2021). A half-day flowering pattern helps plants sharing pollinators in an oceanic island community. *Journal of Tropical Ecology*, 37(1), 16-25. <https://doi.org/10.1017/S0266467421000055>

- Wang, Y. Q., Zhang, D. X., & Chen, Z. Y. (2004). Pollen histochemistry and pollen: ovule ratios in Zingiberaceae. *Annals of Botany*, 94(4), 583-591. <https://doi.org/10.1093/aob/mch177>
- Wani, I. A., Verma, S., Ahmad, P., El-Serehy, H. A., & Hashim, M. J. (2022). Reproductive biology of *Rheum webbianum* Royle, a vulnerable medicinal herb from alpiners of North-Western Himalaya. *Frontiers in Plant Science*, 13, 699645. <https://doi.org/10.3389/fpls.2022.699645>
- 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. <https://doi.org/10.2307/2265575>
- Weir, J. C., & Phillimore, A. B. (2024). Buffering and phenological mismatch: A change of perspective. *Global Change Biology*, 30(5), e17294. <https://doi.org/10.1111/gcb.17294>
- Wilcock, C., & Neiland, R. (2002). Pollination failure in plants: why it happens and when it matters. *Trends in Plant Science*, 7(6), 270-277. [https://doi.org/10.1016/S1360-1385\(02\)02258-6](https://doi.org/10.1016/S1360-1385(02)02258-6)
- Williams-Linera, G., & Meave, J. (2002). Patrones fenológicos (phenological patterns). In: *Ecología y conservación de bosques neotropicales (Ecology and conservation of Neotropical forests)* San Jose, Costa Rica: Libro Universitario Regional. Guariguata, M.R. and Katan, G.H. (eds). pp. 407-431.
- Wilson, Z. A., Song, J., Taylor, B., & Yang, C. (2011). The final split: the regulation of anther dehiscence. *Journal of Experimental Botany*, 62(5), 1633-1649. <https://doi.org/10.1093/jxb/err014>
- Wolcott, K. A., & Vulinec, K. (2012). Bat activity at woodland/farmland interfaces in central Delaware. *Northeastern Naturalist*, 19(1), 87-98. <https://doi.org/10.1656/045.019.0107>
- Wong, M. K., & Didham, R. K. (2024). Global meta-analysis reveals overall higher nocturnal than diurnal activity in insect communities. *Nature Communications*, 15(1), 3236. <https://doi.org/10.1038/s41467-024-47645-2>
- Woodward, F. L. (1987). *Climate and plant distribution*. Cambridge studies in ecology. Cambridge University Press, Cambridge.
- Wright, J. S. (2002). Plant diversity in tropical forests: a review of mechanisms of species coexistence. *Oecologia*, 130, 1-14. <https://doi.org/10.1007/s004420100809>
- Wu, J. Z., Lin, Y., Zhang, X. L., Pang, D. W., & Zhao, J. (2008). IAA stimulates pollen tube growth and mediates the modification of its wall composition and structure in *Torenia fournieri*. *Journal of Experimental Botany*, 59(9), 2529-2543. <https://doi.org/10.1093/jxb/ern119>
- Wyatt, R., & Lipow, S. R. (2021). Reproductive biology of *Mimosa microphylla* and *Albizia julibrissin* (Fabaceae: Caesalpinioideae) with a new explanation for the evolution of polyads, restricted stigmas, and polycarpelly in the mimosoid

- clade1. *The Journal of the Torrey Botanical Society*, 148(2), 97-108.
<https://doi.org/10.3159/TORREY-D-20-00042.1>
- Xiang, W. Q., Malabrigo Jr, P. L., Tang, L., & Ren, M. X. (2022). Limited-distance pollen dispersal and low paternal diversity in a bird-pollinated self-incompatible tree. *Frontiers in Plant Science*, 13, 806217.
<https://doi.org/10.3389/fpls.2022.806217>
- Xiao, D. X., & Xu, F. X. (2006). Megasporogenesis and development of female gametophyte in *Manglietia decidua* (Magnoliaceae). *Annales Botanici Fennici*, 43(6), 437-444.
- Xiao, Y., Li, X., Cao, Y., & Dong, M. (2016). The diverse effects of habitat fragmentation on plant–pollinator interactions. *Plant Ecology*, 217, 857-868.
<https://doi.org/10.1007/s11258-016-0608-7>
- Xu, X., Ren, Z. X., Trunschke, J., Kuppler, J., Zhao, Y. H., Knop, E., & Wang, H. (2021). Bimodal activity of diurnal flower visitation at high elevation. *Ecology and Evolution*, 11(19), 13487-13500. <https://doi.org/10.1002/ece3.8074>
- Yamamoto, M., & Del-Claro, K. (2008). Natural history and foraging behavior of the carpenter ant *Camponotus sericeiventris* Guérin, 1838 (Formicinae, Campotonini) in the Brazilian tropical savanna. *Acta Ethologica*, 11(2), 55-65.
<https://doi.org/10.1007/s10211-008-0041-6>
- Yaqoob, U., & Nawchoo, I. A. (2016). Reproductive ecology of an endangered monocarpic herbaceous perennial, *Ferula jaeschkeana* Vatke. *Tropical Ecology*, 57(4), 849-864.
- Young, A. M., Kodabalagi, S., Brockmann, A., & Dyer, F. C. (2021). A hard day's night: Patterns in the diurnal and nocturnal foraging behavior of *Apis dorsata* across lunar cycles and seasons. *PloS One*, 16(10), e0258604.
<https://doi.org/10.1371/journal.pone.0258604>
- Young, A., Gomez-Ruiz, P., Pena, J., Uno, H., & Jaffé, R. (2018). Wind speed affects pollination success in blackberries. *Sociobiology*, 65(2), 225-231.
<https://doi.org/10.13102/sociobiology.v65i2.1620>
- Younis S., Shaheen S., Harun N., Abbas M., Ahmad M., Hussain K., Khan F. (2021). Application of multimicroscopic techniques (LM and SEM) in comparative palynological study of Asteroideae members, inhabited in Pakistan. *Microscopy Research and Technique*, 84(5), 1063-1077. <https://doi.org/10.1002/jemt.23667>
- Zhang, K., He, C., Wang, S., & Hou, X. (2022). Influence of pollination methods on fruit development, fruit yield and oil quality in oil tree peony. *Scientia Horticulturae*, 295, 110877. <https://doi.org/10.1016/j.scienta.2022.110877>
- Zhang, M., Zhao, J., & Hoshino, Y. (2023). Deep learning-based high-throughput detection of in vitro germination to assess pollen viability from microscopic images. *Journal of Experimental Botany*, 74(21), 6551-6562.
<https://doi.org/10.1093/jxb/erad315>

- Zhang, X. L., Gituru, R. W., Yang, C. F., & Guo, Y. H. (2009). Variations of floral traits among different life forms illustrate the evolution of pollination systems in *Potamogeton* species from China. *Aquatic Botany*, 90(2), 124-128. <https://doi.org/10.1016/j.aquabot.2008.07.006>
- Zhang, Y., & Steiner, A. L. (2022). Projected climate-driven changes in pollen emission season length and magnitude over the continental United States. *Nature Communications*, 13(1), 1234. <https://doi.org/10.1038/s41467-022-28764-0>
- Zhao, W., Hou, Q., Qi, Y., Wu, S., & Wan, X. (2023). Structural and molecular basis of pollen germination. *Plant Physiology and Biochemistry*, 108042. <https://doi.org/10.1016/j.plaphy.2023.108042>
- Zhong, S., Zhao, P., Peng, X., Li, H. J., Duan, Q., & Cheung, A. Y. (2024). From gametes to zygote: mechanistic advances and emerging possibilities in plant reproduction. *Plant Physiology*, 195(1), 4-35. <https://doi.org/10.1093/plphys/kiae125>

BRIEF BIODATA OF THE CANDIDATE

NAME : **Akoijam Benjamin Singh**
FATHER'S NAME : Ak. Ibotomba Singh
MOTHER'S NAME : Ak. Pusparani Devi
DATE OF BIRTH : 18.03.1995
NATIONALITY : Indian
PERMANENT ADDRESS : Bamon Kampu Mayai Leikai, Imphal East,
Manipur - 795008
MOBILE NO : +917005247972, +918794191413
EMAIL ADDRESS : benjakoijam6@gmail.com

EDUCATIONAL QUALIFICATION

Sl.no.	Degree	Subject	Board/University	Year	CGPA
1.	B.Sc.	Forestry	CAU (I)	2016	8.25
2.	M.Sc.	Forestry	Manipur University	2018	8.5
3.	NET	Agroforestry	ASRB-ICAR	2018	-

LIST OF PUBLICATION (Research paper/ Book chapter/ Popular article):

1. **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. <https://doi.org/10.1016/j.jnc.2024.126742>
2. **Singh, A. B.**, Singh, P. D., Vanlalmalsawmropuia, H., Kumar, S., Khanduri, V. P., & Kumar, K. S. (2024). Traditional uses and pharmacological activities of *Sterculia villosa* Roxb.-an underutilized tree of south east Asia. Ethnobotany Research and Applications, 27, 1-23. <http://dx.doi.org/10.32859/era.27.18.1-23>
3. **Benjamin, A.**, Dilip, S., Ranibala, G., & Chanu, N. B. (2019). Effect of seed size, pre-sowing treatments and potting mixture on seedlings growth character and biomass production under nursery conditions of *Terminalia chebula* Retz. Indian Journal of Current Science, 7(4), 1502-1507. <https://dx.doi.org/10.22271/chemi>
4. Chanu, N. B., Julia, T., **Singh, A. B.**, & Hazarika, B. (2025). Natural Farming: A Sustainable Way towards Doubling Farmers' Income. Journal of Experimental Agriculture International, 47(2), 159-171. <https://dx.doi.org/10.9734/jeai/2025/v47i23277>
5. Chanu, N. B., **Singh, A. B.**, & Singh, M. C. (2023). Microwave assisted catalysis for biofuel production. In Bioenergy Engineering. Woodhead Publishing.
6. **Singh, A. B.**, Phom, H. P., Vanlalmalsawmropuia, H., Kumar, S., Khanduri, V. P., Kumar, K. S. (2025). Agrobiodiversity in Traditional Land Use Systems of North East Indian Part of Indo-Burma Hotspot. In Biodiversity Hotspot of the Indo-Burma Region. Apple Academic Press.
7. **Singh, A. B.**, & Kumar, K. S. (2023). Nutritive Value and Health Benefits of Yongchak (*Parkia timoriana*). Just Agriculture, 3 (9).
8. **Singh, A. B.**, & Kumar, K. S. (2023). Study on Biotic Stress in Yongchak (*Parkia timoriana*) in Northeast Region of India. Just Agriculture, 3 (10).
9. **Singh, A. B.**, & Kumar, K. S. (2023). Significance of potting mixture in successful establishment of nursery. Van Sangyan, 10 (6), 26.

RESEARCH EXPERIENCE:

1. Working as Junior Research Fellow (JRF), Department of Forestry, Mizoram University from December 2020 to December 2022.
2. Working as Senior Research Fellow (SRF), Department of Forestry, Mizoram University from December 2022 to December 2023.

MAJOR AWARDS/ RECOGNITION AT NATIONAL/ INTERNATIONAL LEVEL:

1. Awarded “**Governor’s Gold Medal**” for securing First Class First in M.Sc., 2018
2. Awarded “**Nongthombam (O) Tombi Devi Memorial Gold Medal**” for securing First Class First in M.Sc., 2018
3. Awarded “**M. Borajao Singh and M.(O) Amudombi Devi Memorial Gold Medal**” for securing First class in CGPA in the School of Human & Environmental Sciences, 2018.
4. Awarded **2nd best oral presenter** for paper presentation on the topic “Effect of seed size and pre-sowing treatment on germination parameters” in the three days International Conference on “Biodiversity, Biogeochemistry and Ecosystem Sustainability in Changing Environment” jointly organized by Department of Forestry, Mizoram University and Indian Ecological Society from 14th to 16th June, 2023.

ORAL/POSTER PRESENTED:

1. Presented research paper entitled “**Impact of climate change on reproductive developmental phases of crop plants**” in the two days National Seminar on “Strengthening Environmental Health: Role of Society, Science & Technology” organized by Department of Rural Technology and Social Development, Guru Ghasidas Vishwavidyalaya, Bilaspur (C.G.) from 26th - 27th September 2022.
2. Presented research paper entitled “**Role of Pollinators in Reproductive Success of Agroforestry trees**” in the three days International Conference on “Global Approaches in Agriculture and Allied Sciences for Sustainability, Food Security and Livelihood” organized by Samagra Vikas Evam Paryavaran Sanrakshan Samiti,

Prayagraj; Maharaja Agrasen Himalayan Garhwal University, Uttarakhand; and Agra College, Uttar Pradesh from 21st to 23rd January, 2023.

3. Presented research paper entitled “**Effect of seed size and pre-sowing treatment on germination parameters**” in the three days International Conference on “Biodiversity, Biogeochemistry and Ecosystem Sustainability in Changing Environment” jointly organized by Department of Forestry, Mizoram University and Indian Ecological Society from 14th – 16th June, 2023.
4. Presented research paper entitled “**Role of plant growth regulators in pollen germination and pollen tube growth**” on the occasion of three days International Conference on “Innovative Approaches in Agriculture, Horticulture and Allied Sciences” at SGT University, which is jointly organized by SGT University, Gurugram and ISAHRD, Chandigarh from 29th to 31st March, 2023.

WORKSHOP/ SEMINAR/ REFERESHER COURSE/ TRAINING:

1. Completed 21 days Refresher Course on Agroforestry from 17th July to 6th August 2023 which was organized by Indian Society of Agroforestry in collaboration with Indian Council for Agricultural Research (ICAR) and Central Agroforestry Research Institute (CAFRI) and supported by Ministry of Agriculture and Farmers Welfare, Government of India.
2. Attended 21 days scientific online training on “Bio-input Technologies based Entrepreneurship for Sustainable Livelihood in Agriculture” from 7th to 27th January, organized by College of Horticulture and Forestry, CAU, Pasighat, Arunachal Pradesh, College of PG Studies in Agricultural Sciences, CAU, Umiam, Meghalaya and Assam Agricultural University, Jorhat, Assam.
3. Attended High-end workshop on “Quality Control and Standardization of Herbal Raw Materials for Value Addition and Sustainable Development in North East” from 16th to 21st September, 2022 organized by Department of Horticulture, Aromatic and Medicinal Plants, Mizoram University.
4. Attended national training on “Geospatial Technology Application in Forestry” from 26th to 28th November 2020 organized by College of Horticulture and Forestry, CAU, Pasighat, Arunachal Pradesh, under Institutional Development Plan of National Agricultural Higher Education Project.

5. Attended a training program on “Climate Change Adaptation for Natural Resource Management for the State of Mizoram” from 11th to 15th March, 2021 sponsored by Department of Science and Technology, Government of India at Mizoram University.
6. Attended 3 Days Web Workshop cum Training on Edible Insect “Edible insect and non-conventional foods as a nutrient pack and livelihood security” from 27th to 29th January 2021 organized by the College of Horticulture and Forestry, Central Agricultural University (Imphal), Pasighat, Arunachal Pradesh funded by National Mission for Himalayan Mission Studies, (NMHS), MoEF, GBPNIHESD, Almora,
7. Attended online webinar on “Herbal medicine to combat the threatening pandemic diseases a scope for future startup” organized by the College of Horticulture and Forestry, Central Agricultural University (Imphal), Pasighat, Arunachal Pradesh, under Institutional Development Plan of National Agricultural Higher Education Project held on 01st and 02nd February 2022.
8. Attended the UGC STRIDE Workshop on “Statistical Data Analysis and Interpretation” held from 13th January 2021 to 18th January 2021 at the Mizoram University, Aizawl.
9. Attended short term course on Research and Publication Ethics held from 01st – 07th October 2021 organized by UGC Human Resource Centre, Mizoram University.
10. Attended seven days virtual training on “Success Master class: Personality Development with Soft Skills Learning” organized by the College of Horticulture and Forestry, Central Agricultural University (Imphal), Pasighat, Arunachal Pradesh, under Institutional Development Plan of National Agricultural Higher Education Project held on 1st to 8th February 2022.
11. Attended “PCR Training Program” conducted by Eppendorf India Limited, Chennai from 29th -31st, August 2022.
12. Attended two days online training on “Plant Biotechnology” organized by Genetics and Tree Improvement Division, Tropical Forest Research Institute, Jabalpur from 5th to 6th January 2022.

13. Attended “Hands on Workshop in Molecular Phylogenetics” from 9th to 14th March, 2023 sponsored by DBT- Advanced State Level Biotech Hub and Mizoram University.
14. Attended 7 days Faculty Development Program on “Research Methodology, Bibliometric Analysis and Data Analysis Using R” from 22nd -28th July 2023 which was jointly organized by Society of Education, India; University of Agricultural Sciences, Raichur; European Laser Academy, Germany and Genome Biotech, Mathura in association with Office of the Principal Scientific Advisor to the Government of India under Waste to Wealth Mission.
15. Attended one-week National Workshop on “Research Methods using SPSS” organized by Swami Vivekananda University in collaboration with SPSS South Asia during 6th to 10th February 2023.

PARTICULARS OF THE CANDIDATE

NAME OF CANDIDATE : Akoijam Benjamin Singh
DEGREE : Ph.D.
DEPARTMENT : Forestry
TITLE OF THESIS : Reproductive biology of *Parkia timoriana* (DC.) Merr. under silvihorticultural system in Mizoram, North-East India.
DATE OF ADMISSION : 20.08.2021
APPROVAL OF RESEARCH PROPOSAL
1. DRC : 19.04.2022
2. BOS : 26.05.2022
3. SCHOOL BOARD : 10.06.2022
MZU REGISTRATION NUMBER : 2200139
Ph.D. REGISTRATION NUMBER & DATE : MZU/Ph.D./1910 of 20.08.2021
EXTENTION (IF ANY) : N/A

(Prof. U. K. Sahoo)

Head

Department of Forestry

Mizoram University

Aizawl, Mizoram

ABSTRACT

**REPRODUCTIVE BIOLOGY OF *PARKIA TIMORIANA* (DC.)
MERR. UNDER SILVIHORTICULTURAL SYSTEM IN
MIZORAM, NORTH-EAST INDIA**

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

AKOIJAM BENJAMIN SINGH

MZU REGISTRATION No.: 2200139

Ph.D. REGISTRATION No.: MZU/Ph.D./1910 of 20.08.2021



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

**REPRODUCTIVE BIOLOGY OF *PARKIA TIMORIANA* (DC.) MERR.
UNDER SILVIHORTICULTURAL SYSTEM IN MIZORAM, NORTH-EAST
INDIA**

By

AKOIJAM BENJAMIN SINGH

Department of Forestry

Supervisor

Dr. NAGARAJ HEGDE

Joint Supervisor

Dr. KEWAT SANJAY KUMAR

Submitted

**In partial fulfillment of the requirement of the Degree of Doctor of Philosophy
in Forestry of Mizoram University, Aizawl.**

Introduction

Tropical ecosystems exhibit extraordinary biological diversity and complex ecological networks that sustain global biodiversity and crucial ecosystem functions. Central to the sustainability and resilience of these ecosystems is the reproductive biology of constituent plant species, which governs population viability, genetic diversity, and ecosystem dynamics through flowering phenology and pollination processes. *Parkia timoriana*, a vital evergreen tree species native to the tropical forests of Northeast India, occupies diverse elevational gradients and performs significant ecological roles, including providing food resources and habitat to myriad faunal species. Its reproductive success is strongly influenced by an intricate interplay of biotic interactions and environmental factors.

In recent decades, rapid anthropogenic activities such as unregulated harvesting of high demand plant species, deforestation, and widespread habitat fragmentation have profoundly altered forest ecosystems. These actions impinge upon reproductive dynamics by fragmenting populations and disrupting complex plant-pollinator interactions, leading to genetic bottlenecks, diminished resilience, and population declines. Such degradation triggers cascading effects that reverberate through trophic networks, endangering biodiversity and ecosystem functionality.

Compounding these pressures, climate change introduces variability in temperature regimes, precipitation patterns, and seasonality, thereby destabilizing phenological synchrony crucial for reproductive timing. Changes in flowering and fruiting schedules can misalign with pollinator activity windows, causing declines in reproductive success and threatening long term survival. This is especially critical in tropical forests, where many plants and their pollinators have evolved highly specialized and interdependent relationships.

Understanding the reproductive biology of *P. timoriana* including its floral morphology, phenological patterns, pollinator assemblages, pollen characteristics, and physiological constraints is imperative for developing effective conservation strategies. The species shows floral dimorphism, with distinct morphs producing nectar or pollen, each contributing uniquely to the reproductive process. Investigating

these morphs' roles, alongside the dynamics of diurnal and nocturnal pollinator guilds, offers insight into the species' reproductive ecology.

Further, detailed investigations into pollen morphology, viability, and the influence of phytohormonal treatments on pollen germination and pollen tube growth advance our grasp of the physiological determinants of reproductive success. Integrating long-term field phenological monitoring with laboratory physiological assays and environmental modeling forms a robust framework to decipher *P. timoriana*'s reproductive resilience under ongoing ecological changes. This knowledge supports biodiversity conservation, sustainable resource management, and genetic preservation in tropical forests.

The present investigation titled “Reproductive biology of *Parkia timoriana* (DC.) Merr. under silvihorticultural system in Mizoram, North-East India” was conducted during 2021-2024 at Mizoram with the following objectives:

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

Methodology

The study employed an integrative, multidisciplinary approach over a three-year period (2021–2024), encompassing three ecologically representative sites along a pronounced altitudinal gradient within Mizoram: low altitude (Sairang), mid altitude (Tanhrlil), and high altitude (Reiek). These sites were selected to capture climatic and ecological heterogeneity, allowing comparative analysis of reproductive patterns and environmental influences.

Phenological observations adhered to the BBCH scale, a standardized coding system for developmental stages focusing on key reproductive milestones from inflorescence initiation (stage 5) to fruit maturation (stage 8). Parameters such as flowering onset,

peak, duration, fruit set initiation, and maturity were recorded at both individual plant and population levels. Flowering synchrony indices were calculated to quantify the temporal overlap of flowering events within populations, aiding in interpretation of reproductive timing and potential for cross-pollination.

Comprehensive floral biology assessments encompassed continuous diurnal and nocturnal observation sessions to record anthesis timing, stigma receptivity duration, and anther dehiscence patterns. These traits are pivotal to understanding pollinator access and effectiveness. Detailed morphological studies employed light and scanning electron microscopy to characterize pollen grain structure, polyad configuration, surface ornamentation, and aperture placement, essential for inferring dispersal and compatibility attributes.

Insect and mammalian pollinator assemblages were surveyed within the same periods, applying standardized 2-hour observational windows across 24-hour cycles. Taxonomic identification of visitors included bees, wasps, ants, moths, and bats. Visitor frequency, behavioral modes, and flower handling were meticulously recorded to determine pollinator diversity, temporal niche partitioning, and pollination effectiveness.

Experimental pollination trials included controlled hand pollination to delineate breeding system components - self-pollination (autogamy), geitonogamy (within-plant cross-pollination), xenogamy (cross-pollination involving different individuals), alongside open pollination controls and exclusion treatments. Fruit and seed set following each treatment quantified reproductive outcomes, indicating the relative success of each pollination strategy.

Climatic variables were statistically analyzed for correlations with reproductive phenological variables through Spearman's rank and multiple regression models to link phenological and reproductive metrics with environmental variables, enabling identification of key drivers influencing plant reproductive events.

Aerobiological sampling was conducted with slide-hanging techniques and impaction samplers (e.g., GRIPS-99M), capturing airborne pollen concentrations at hourly

intervals. This quantified temporal fluctuations in pollen dispersal dynamics, critical for understanding gene flow processes.

Laboratory-based physiological analyses assessed pollen viability using multiple techniques- TTC, FDA, and Alexander stain, across both floral morphs. *In vitro* pollen germination assays evaluated effects of varying sucrose concentrations (5%, 10%, 15%, 20%) and incubation temperatures (15°C, 20°C, 25°C, 30°C). Subsequent experiments examined exogenous application of phytohormones - indole-3-acetic acid (IAA), indole-3-butyric acid (IBA), gibberellic acid (GA₃), and kinetin, at multiple concentrations to elucidate their influence on pollen germination percentage and tube elongation, informing optimal conditions for reproductive interventions.

Results

The study revealed significant spatio-temporal patterns in phenology and reproductive biology across the altitudinal gradient and inter-annual variability. At the low elevation site, flowering onset exhibited a consistent delay from early November to mid-November over the three years, likely linked to increasing local temperatures and altered microclimatic conditions. By contrast, the mid and high elevation sites showed relatively stable flowering schedules, signifying topographical buffering from climatic variability. Flowering duration averaged between 50–74 days per individual and extended beyond 80 days at the population level, reflecting flexibility in reproductive timing. High flowering synchrony indices (~0.80–0.85) across all sites indicated substantial overlap in floral availability conducive to synchronous pollinator attraction and cross-pollination.

Anthesis mostly occurred between 17:00 and 19:00 hours, coinciding with peak foraging periods of diurnal pollinators such as *Apis cerana indica*, *Bombus spp.*, and *Trigona spp.*, as well as early nocturnal activity by bats. Stigma receptivity was prolonged, spanning 1–2 days post-anthesis, thereby enhancing the pollination window and accommodating diverse pollinator activity periods. Anther dehiscence closely correlated with environmental parameters- temperature and relative humidity, suggesting climatic cues modulate pollen release timing.

Pollinator assemblages demonstrated extensive taxonomic diversity, with distinct temporal niches; diurnal visits were dominated by bees, wasps, and ants, whereas nocturnal visitors comprised moths, bats, and some scarab beetles. Statistical analyses established moderate correlations between pollinator visitation rates and environmental variables such as temperature and wind velocity, while humidity had an inhibitory effect on certain taxa. Notably, slight declines in visitation frequencies across years potentially reflect emerging ecosystem stressors.

Microscopic examination revealed pollen grains organized in cavitate polyads, consisting of tightly clustered individual pollen grains. Each polyad typically comprises 32 pollen grains arranged in a spherical or slightly ellipsoidal structure. The pollen exine surface was predominantly smooth with occasional minor depressions indicative of apertures, consistent with pollinator-mediated dispersal adaptations. Viability assessments yielded higher percentages in pollen from hermaphrodite flowers than nectar-producing flowers, highlighting functional differentiation among floral morphs.

In vitro germination tests showed the highest *in vitro* pollen germination rate and robust pollen tube elongation occurred at 15% sucrose concentration and 25°C incubation temperature. Application of plant growth regulators revealed that IBA and GA significantly enhanced pollen germination rates and pollen tube growth, whereas kinetin exhibited a hormetic effect, stimulating growth at moderate but not elevated concentrations. These findings reveal hormonal modulation potential for optimizing pollen performance.

Pollination experiments unequivocally demonstrated reliance on biotic vectors; open pollination treatments produced the highest fruit and seed set, contrasting with minimal fruiting in selfing and pollinator-exclusion treatments. Xenogamous pollination was most effective, confirming an outcrossing breeding system that depends heavily on diverse pollinator assemblages. Aerobiological analyses reported diel patterns in airborne pollen concentrations, with nocturnal and early morning peaks aligning with stable atmospheric conditions favorable for pollen viability and transport.

Discussion

The progressively delayed flowering at the lower elevation site reflects increasing thermal stress and altered microclimatic factors consistent with global climate change impacts documented in tropical forests worldwide. Elevated temperature regimes can inhibit physiological processes controlling floral development, thereby shifting phenological events and risking temporal mismatches with pollinator availability. The relative phenological stability observed at mid and high altitudes suggests microclimatic refugia that buffer the reproductive timing of populations.

Synchronization of anthesis with peak pollinator activity demonstrates an evolved mutualism designed to maximize reproductive success. Extended stigma receptivity accommodates temporal variability in pollinator access, thereby mitigating the risk of reproductive failure due to fluctuating pollinator abundance or activity. This reproductive plasticity is particularly vital in changing environments.

The diverse pollinator assemblage including bees, ants, moths, and bats, facilitates temporal complementarity in pollen transfer, ensuring reproductive continuity across varying climatic conditions and diurnal periods. However, observed declines in visitation rates signal emerging vulnerabilities. Loss and alteration of pollinator communities, exacerbated by habitat fragmentation, pesticide use, and climate change, jeopardize essential mutualistic relationships critical for plant reproduction.

The exclusive reliance of *P. timoriana* on biotic pollinators and the absence of autonomous self-fertility increase its susceptibility to pollinator declines. Such dependence necessitates conservation prioritization of pollinator habitats to maintain functional ecosystems. The beneficial effects of cross-pollination over geitonogamous or autogamous pollination underscore the evolutionary advantage of outcrossing, promoting genetic diversity and population fitness foundational to forest resilience.

Variations in floral traits, including flower and nectar production, reveal adaptive responses to environmental gradients. Increased reproductive allocation at higher elevations likely reflects favorable moisture availability and cooler temperatures enhancing resource availability. These plastic responses may be critical for adaptation under climatic stress.

Aerobiological findings highlight the importance of nocturnal and early morning pollen release windows, which align with optimal atmospheric conditions lower temperature, stable humidity, and minimal turbulence for effective pollen dispersal. These environmental factors mediate reproductive connectivity and gene flow.

In vitro assessments emphasize the pivotal influence of temperature and exogenous growth regulators in pollen germination and pollen tube growth, providing promising avenues for ex situ conservation and nursery propagation programs. Plant growth regulators like IBA and GA could significantly optimize pollen performance in controlled breeding contexts.

Integrated conservation strategies must address habitat restoration, microclimate stabilization, and pollinator protection to safeguard *P. timoriana*'s reproduction in the face of escalating ecological threats. Long-term phenological monitoring coupled with environmental modeling will enhance predictive capabilities and inform adaptive management, crucial for maintaining tropical biodiversity and ecosystem services.

Conclusion

This comprehensive study elucidates the multifaceted reproductive ecology of *P. timoriana*, revealing its sensitivity to microclimatic variation, reliance on a diverse and complementary pollinator community, and evolutionary adaptations for maximizing reproductive success. Phenological patterns demonstrate the impacts of climate variability along elevation gradients, highlighting risks associated with delayed flowering and potential mismatches with pollinator activity, particularly at lower elevations.

The species exhibits floral morphologies and physiological traits that collectively promote efficient outcrossing, including precise anthesis timing, prolonged stigma receptivity, and pollen traits supporting effective dispersal. Pollinator observations affirm the importance of both diurnal and nocturnal animals including key bee species and bats in sustaining reproductive outcomes.

Environmental drivers such as soil moisture, temperature, humidity, and wind act as critical determinants of phenological events and pollen dispersal, underlining the need

for conservation strategies integrating habitat quality and climatic resilience. Hormonal modulation of pollen germination offers a practical tool for conservation breeding and ex situ propagation efforts.

Given the current biodiversity crisis and rapidly changing climate, protecting *P. timoriana* requires coordinated measures fostering pollinator networks, habitat integrity, and adaptive management based on empirical, long term data. This research contributes critical insights to inform such efforts, aiding in the preservation of this keystone species and the ecosystems it supports for future generations.