

Seasonal Dynamics and Diversity of Airborne Pollen in Srinagar Valley, Garhwal Himalaya: Influence of Meteorological Variables on Aeroallergen Spectrum

Shikha Arya³, Prabhawati Tiwari³, Ajendra Singh Bagri¹, Alok Sagar Gautam²,

¹Department of Environmental Science, HNB Garhwal University, BGR Campus Pauri (Garhwal) - 246174, Uttarakhand, India

²Department of Physics, HNB Garhwal University, Srinagar (Garhwal) - 246174, Uttarakhand, India

³Department of Botany & Microbiology, HNB Garhwal University, Srinagar (Garhwal) - 246174, Uttarakhand, India

Corresponding author: Ajendra Singh Bagri

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Abstract

This study presents a comprehensive assessment of airborne pollen and fungal spore diversity, seasonal variation, and their correlation with meteorological parameters in the Srinagar Valley of Garhwal Himalaya, Uttarakhand. Daily air samples collected from May 2019 to April 2020 using a digital Rotorod sampler revealed 52 pollen-producing taxa grouped into 35 morphotypes and 23 fungal spore types from 20 genera. Dominant airborne pollen included *Poaceae* (22.43%), *Pinus* (17.36%), *Parthenium hysterophorus* (12.1%), and *Cannabis sativa* (11.5%), while *Alternaria*, *Cladosporium*, and *Curvularia* were the most frequent fungal spores. Pollen concentrations peaked during the spring season, showing a strong positive correlation with temperature, while rainfall and humidity were negatively correlated. These findings highlight the region's rich aerobiological diversity and its potential impact on respiratory health. The study emphasizes the need for continuous pollen monitoring and public health preparedness, especially during high pollen seasons.

Keywords: Aerobiology, Aero-allergy, Pollen concentration, Meteorological parameters, Rainfall, Pearson correlation

Introduction

The Earth's atmosphere is a dynamic medium that transports a diverse range of biological particles, collectively referred to as atmospheric bioaerosols. These include pollen grains, fungal spores, bacteria, and plant fragments, which play crucial ecological roles in

pollination, species dispersal, and microbial interactions. Simultaneously, they pose significant public health risks due to their allergenic potential (Pawankar et al., 2021; Damialis et al., 2021). Among these, pollen grains from anemophilous (wind-pollinated) plant species are particularly prominent due to their aerodynamic properties, abundance in the air, and well-documented association with allergic diseases such as rhinitis, conjunctivitis, and asthma (Ziska et al., 2019; Cecchi et al., 2022). The discipline of aerobiology, which examines the sources, dispersal, and impacts of airborne biological particles, has gained renewed attention in the era of climate change. Recent studies show that climatic shifts are altering pollen phenology, geographic distributions, and allergenicity (Ziello et al., 2023; Frenguelli et al., 2023). Longitudinal data from across the Northern Hemisphere indicate that pollen seasons are becoming longer and more intense due to rising temperatures and elevated atmospheric CO₂ (Damialis et al., 2021; Ziska et al., 2019). These changes carry profound implications for the timing and severity of allergic responses and emphasize the importance of localized monitoring and predictive modeling.

In the Indian context, the vast ecological heterogeneity and diverse climatic zones provide a unique natural laboratory for aerobiological research. Studies from metropolitan regions such as Delhi, Bengaluru, and Kolkata have identified Poaceae, Asteraceae, Amaranthaceae, and Moraceae as the dominant allergenic pollen families (Sharma & Ghosh, 2022; Kumar et al., 2023; Bhat et al., 2024). However, such studies are unevenly distributed across the country. Notably, the Indian Himalayan Region (IHR), despite its ecological sensitivity and high biodiversity, remains underrepresented in aerobiological surveys. This research gap is especially pronounced in mid-altitude zones like the Srinagar Valley in the Garhwal Himalaya. This region, characterized by steep altitudinal gradients and subtropical montane forests, exhibits a rich floristic composition and complex pollen dispersal patterns. Yet, most of the foundational aerobiological work in the Western Himalaya dates back several decades (Singh et al., 1987; Gaur & Kala, 1984), with limited updates despite mounting ecological and health concerns.

Moreover, meteorological variables are critical in modulating pollen production, release, and atmospheric residence time. Parameters such as temperature, relative humidity, precipitation, and wind velocity strongly influence the daily and seasonal fluctuations in pollen concentration (Almeida et al., 2018; Tripathi et al., 2022). For instance, rain events tend to reduce airborne pollen through washout, while elevated temperatures and high wind speeds enhance pollen liberation and transport over long distances (Cecchi et al., 2022;

Ahmed et al., 2023). As such, integrative aerobiological studies must incorporate meteorological data to accurately interpret temporal pollen trends and their health implications. In response to these knowledge gaps, the present study was undertaken in the Srinagar Valley of the Garhwal Himalaya over a two-year period (2019–2021) with the following objectives: (i) to document the diversity and seasonal variation of airborne pollen taxa; (ii) to evaluate the influence of meteorological parameters on pollen dynamics. This work aims to provide foundational data for developing region-specific aeroallergen advisory systems and to advance our understanding of the ecological and health impacts of airborne pollen in Himalayan ecosystems.

Materials and Methods

Study Area

The present study was conducted in the Srinagar Valley of the Garhwal Himalaya, Uttarakhand, India, specifically at Chauras (30°13'35.81"N, 78°48'11.05"E; 560 m amsl), a campus of Hemvati Nandan Bahuguna Garhwal University (Figure 1). Situated along the right bank of the Alaknanda River, this region lies within the subtropical zone of the Lesser Himalaya and is characterized by complex topography and diverse vegetation. The surrounding flora includes a mosaic of broadleaf deciduous forests, chir pine (*Pinus roxburghii*) stands, thorny shrubs, grasses, and urban greenery. Common wild species include *Acacia* spp., *Aegle marmelos*, *Anogeissus latifolia*, *Bombax ceiba*, *Butea monosperma*, *Cannabis sativa*, *Ficus* spp., *Melia azedarach*, *Parthenium hysterophorus*, and *Woodfordia fruticosa*. Cultivated and avenue species such as *Albizia* spp., *Cupressus torulosa*, *Dalbergia sissoo*, *Ficus elastica*, *Phyllanthus emblica*, and *Tecoma stans* are widespread. Species like *Holoptelea integrifolia*, *Ougeinia oojeinensis*, *Syzygium cumini*, and *Terminalia* spp. occur both in the wild and in cultivated settings. Grasses observed include *Apluda aristata*, *Cynodon dactylon*, *Digitaria* spp., and *Miscanthus nepalensis*.

Methodology

Air Sampling and Pollen Collection: Airborne pollen was collected using a digital Rotorod sampler (Model WMS200) installed at a height of 8 meters on the rooftop of the Department of Botany and Microbiology, Chauras campus. Sampling was conducted daily from Jan 1, 2019, to Dec, 2019. Collection rods were coated with glycerin jelly and replaced hourly. The slides were examined microscopically using the continuous sweep method as outlined by Mandrioli, Comtois, and Levizzani (1998). Pollen grains were

identified at 400 $\times$ magnification using a reference slide library prepared through acetolysis (Erdtman, 1966). Taxa contributing more than 3% to the total annual pollen concentration (APC) were considered dominant (Celenk et al., 2010). To validate micro-regional variations, parallel sampling was conducted at a secondary site across the Alaknanda River in Srikot Gangnali, following the procedural guidelines of Shivpuri (1964).

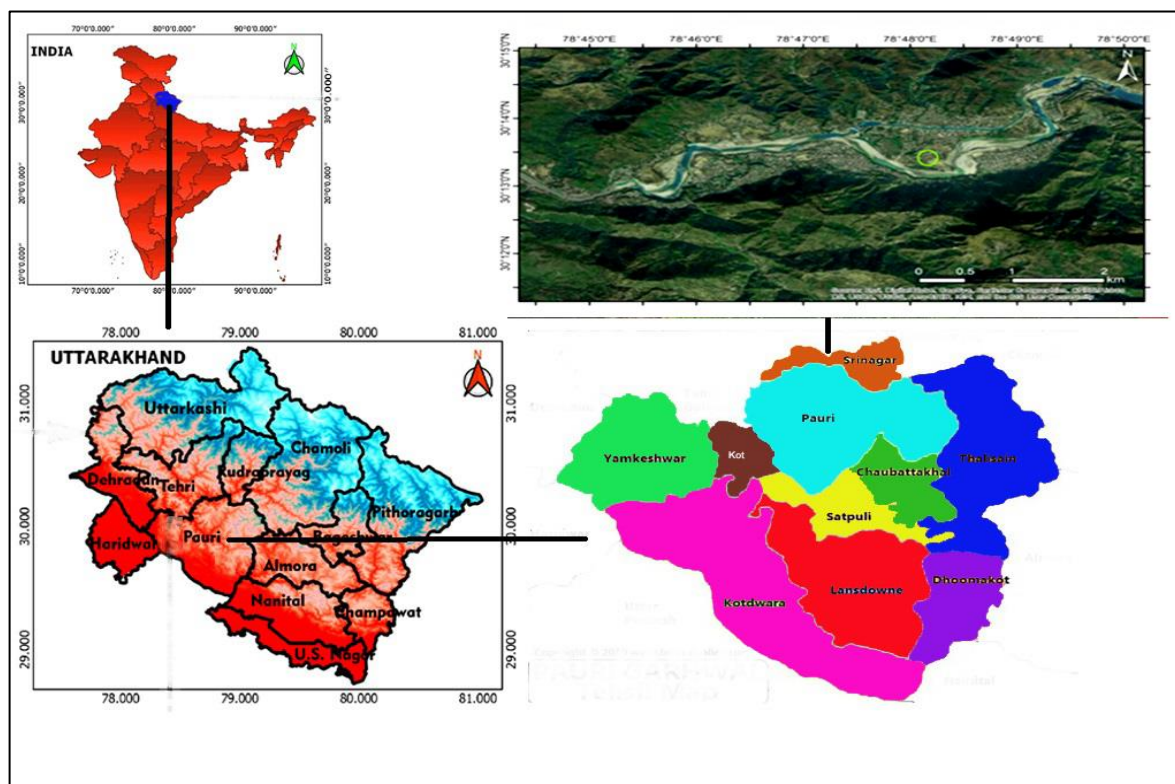


Figure.1. Location map of the study area.

Reference Slide Preparation

Reference slides were prepared using both acetolysed and unacetolysed techniques. Unacetolysed samples were preserved in 70% ethanol, sieved, centrifuged, stained with safranin, and mounted in glycerin jelly. Acetolysis followed Erdtman's (1960) protocol to enhance visibility of exine features.

Microscopic Analysis

Microscopic analysis was conducted under 100 $\times$, 400 $\times$, and 1000 $\times$ magnifications using a Magnus Pro 3.7 microscope. To examine intricate exine architecture (e.g., granulae, reticulations, spinules), selected samples were analyzed under a Scanning Electron Microscope (SEM) using sample preparation techniques described by Falk (1980).

Fungal Spore Identification

Fungal spores collected concurrently were stained with cotton blue and examined microscopically. Identification was performed using morphological keys provided by Lacey and West (2006) and Arora and Jain (2008). Spores were categorized by type and documented monthly.

Meteorological Data Collection

Meteorological parameters temperature, humidity, rainfall, and wind speed—were recorded via a Davis Vantage Pro2 Automatic Weather Station (AWS) installed at the Department of Physics, HNB Garhwal University (Figure 2). Data were logged at one-minute intervals and processed into hourly means using Special Weather Link (v6.0.3) and Aroldis software, following methodologies from Ike (2014), Jenkins (2014), and Sharma et al. (2018). Pearson correlation analyses between pollen concentrations and meteorological variables were conducted in R software using the Hmsc package (v4.4) in line with Feng et al. (2019), Gautam et al. (2020), and Liu et al. (2020).

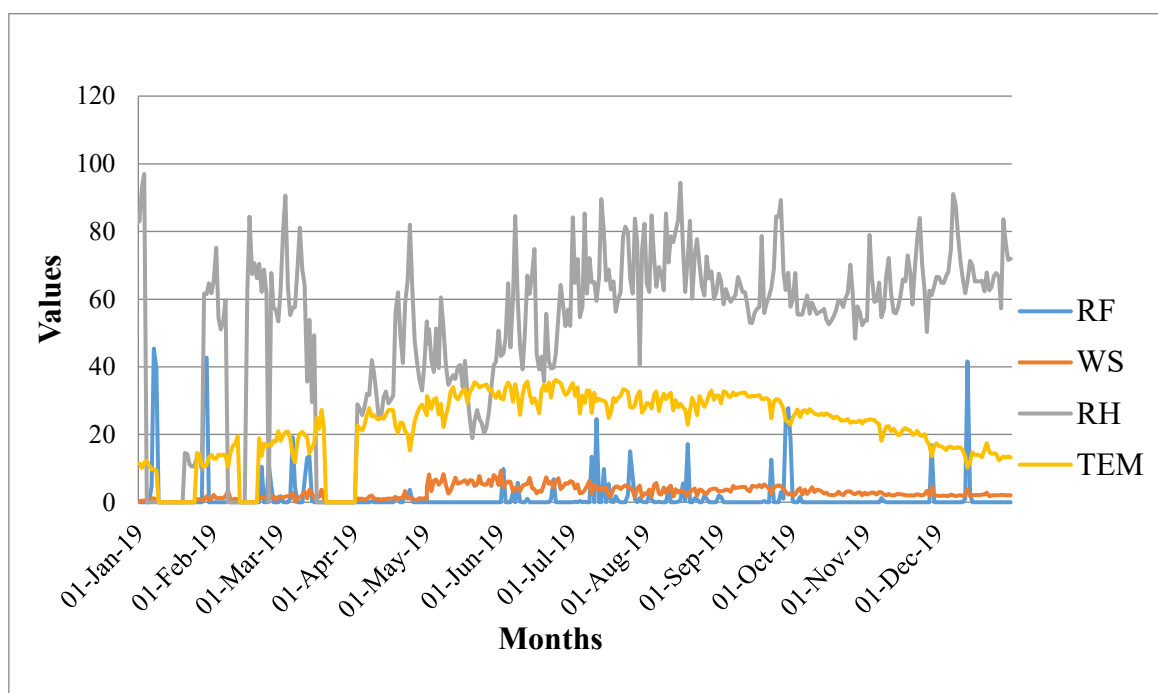


Figure.2. Meteorological parameters of study areas.

Results

Pollen Diversity and Classification: A total of 52 airborne pollen-producing plant species were recorded during the study period (Table1, Figure 5, Plate 1 to 4). These were grouped into 35 distinct pollen morphotypes based on reference slide comparisons and

morphological traits. Due to overlapping features under light microscopy, some pollen particularly from families such as Cupressaceae, Myrtaceae, and Asteraceae could not be identified beyond the family or genus level. Pollen grains that were broken, distorted, or otherwise unidentifiable were categorized as “Unidentified.” Despite these limitations, the study revealed substantial pollen diversity across the sampling area. Dominant morphotypes were identified based on their contribution to the total annual airborne pollen concentration (APC), with a threshold of $\geq 2\%$. The results revealed that the nearly half (48.6%) of the pollen types are anemophilous, explaining their dominance in the air. Entomophilous pollen (45.7%) is also significant, likely due to proximity to ornamental, avenue, and garden plants. Mixed pollination types (5.7%) like palms reflect the ecological diversity of the study area (Figure 3). This distribution emphasizes the dominant role of wind pollinated taxa such as Poaceae, Pinaceae, Cupressaceae, and Amaranthaceae in shaping the aerobiological profile of the valley (Table 1).

Dominant Pollen Types

Thirteen pollen types exceeded the 2% threshold and collectively accounted for 81.74% of the total pollen catch (Figure 4). These include:

Poaceae (grass pollen) – the most prevalent contributor at 22.43%, reflecting wide-ranging grass cover and continuous flowering in the region.

Table1. Possible source plant, pollen types and other details of the identified taxa.

S. No.	Possible source plant	Pollen type	Plant habit	Family	Inflorescence	Flowering period	Mode of pollination
	<i>Acacia nilotica</i> (L.) Willd. ex Delile	<i>Acacia</i> type	Tree	Fabaceae	Globular head	Feb-Apr	A & E
	<i>Acacia catechu</i> Brandis		Tree		Long spike		
	<i>Albizia lebbeck</i> (L.) Benth.	<i>Albizia</i> type	Tree	Fabaceae	Globular head	Feb-Apr	A & E
	<i>A. procera</i> (Roxb.) Benth.						
	<i>Amaranthus viridis</i> L.	<i>Amaranth/Chenopod</i> type	Herb	Amaranthaceae	Spike	Jan-Dec	A
	<i>A. cruentus</i> L.		Herb				
	<i>A. spinosus</i> L.		Herb				
	<i>Chenopodium album</i> L.		Herb				
	<i>Artemisia japonica</i> Thunb	<i>Asteraceae</i> type	Herb	Asteraceae	Head	Jan-Dec	E
	<i>Tagetes minuta</i> L.		Herb				
	<i>Betula alnoides</i> Buch.-Ham. ex D.Don	<i>Betula</i> type.	Tree	Betulaceae	Catkin	Mar-June	A
	<i>Betula utilis</i> D.Don		Tree				
	<i>Bombax ceiba</i> L.	<i>Bombax</i> type	Tree	Malvaceae	Solitary	Jan-Mar	A & E
	<i>Broussonetia papyrifera</i> (L.) L'Hér. ex Vent.	<i>Broussonetia</i> type	Tree	Moraceae	Catkin	Mar-Apr	A
	<i>Cannabissativa</i> L.	<i>Cannabistype</i>	Herb	Cannabaceae	Compound receme	Mar-Nov	A & E
	<i>Cascabela thevetia</i> (L.) Lippold	<i>Cascabella</i> type	Tree	Apocynaceae	Solitary	Jan-Dec	E
	<i>Cassia fistula</i> L.	<i>Cassia</i> type	Tree	Fabaceae	Long drooping receme	Mar-Sep	E
	<i>Senna tora</i> (L.) Roxb.		Shrub		Receme		
	<i>Cedrus deodara</i> (Roxb. ex	<i>Cedrus</i> type	Tree	Pinaceae	Cone	Oct-Dec	A

D.Don) G.Don						
<i>Celtis australis</i> L.	<i>Celtis</i> type	Tree	Cannabaceae	Catkin		A
<i>Cupressus torulosa</i> D.Don ex Lamb.	Cupressaceae type	Tree	Cupressaceae	Cone	Jan-Dec	A
<i>Juniperus</i> spp.		Shrub				
<i>Thuja occidentalis</i> L.		Shrub				
<i>Dalbergia sissoo</i> Roxb. ex DC.	<i>Delbergia</i> type	Tree	Fabaceae	Short spike	Mar-Apr	A & E
<i>Dalbergia latifolia</i> Roxb.		Tree		Short spike		
Grasses	Grass type	Herb	Poaceae	Spike, panicle	Jan-Dec	A
<i>Holoptelea integrifolia</i> (Roxb.) Planch.	<i>Holoptelea</i> type	Tree	Ulmaceae	Compound corymb	Feb-Mar	A
<i>Lannea coromandelica</i> (Houtt.) Merr.	<i>Lannea</i> type	Tree	Anacardiaceae	Catkin	Mar-May	E & A
<i>Mallotus philippensis</i> (Lam.) Müll.Arg.	<i>Mallotus</i> type	Tree	Euphorbiaceae	Catkin	Sep-Nov	A
<i>Mangifera indica</i> L.	<i>Mangifera</i> type	Tree	Anacardaceae	Terminal panicle	Feb-Apr	E
<i>Melia azedarach</i> L.	<i>Melia</i> type	Tree	Meliaceae	Panicle	Mar-Apr	E
<i>Azadirachta indica</i> A.Juss.		Tree				
<i>Mimosa rubicaulis</i> subsp. himalayana (Gamble) H.Ohashi	<i>Mimosa</i> type	Tree	Fabaceae	Globular head	Apr-Aug	A & E
<i>Moringa oleifera</i> Lam.	<i>Moringa</i> type	Tree	Moringaceae	Panicle	Feb-Apr	E
<i>Morus alba</i> L.	<i>Morus</i> type	Tree	Moraceae	Catkin	Feb-Apr	A
<i>Morus serrata</i> Roxb.		Tree		Catkin	Feb-Mar	
<i>Murraya koengii</i> (L.) Sprengel.	<i>Murraya</i> type	Shrub	Rutaceae	Cyme	Mar-Apr	E
<i>Myrica esculenta</i> Buch.-Ham. ex D.Don	<i>Myrica</i> type	Tree	Myricaceae	Catkin		A
<i>Caryota urens</i> L.	Palm type	Tree	Arecaceae	Spadix	Jan-Dec	A

<i>Parthenium hysterophorus</i> L.	<i>Parthenium type</i>	Herb	Asteraceae	Head	Jan-Dec	A & E
<i>Phyllanthus emblica</i> L.	<i>Phyllanthus type</i>	Tree	Phyllanthaceae	Catkin	Feb-Apr	A & E
<i>Pinus roxburghii</i> Sarg.	<i>Pinus type</i>	Tree	Pinaceae	Cone	Mar-June	A
Pteridophyte	Pteridophyte	Herb	Pteridophytes	-	-	-
<i>Quercus leucotrichophora</i> A.Camus	<i>Quercus type</i>	Tree	Fagaceae	Catkin		A
<i>Ricinus communis</i> L.	<i>Ricinus type</i>	Shrub	Euphorbiaceae	Spike	Feb-Mar, Sep-Oct	A
<i>Rumex hastatus</i> D.Don	<i>Rumex type</i>	Herb	Polygonaceae	Terminal receme	Feb-June	A
<i>Rumex dentatus</i> L.		Herb				
<i>Melaleuca citrina</i> (Curtis) Dum.Cours	<i>Mrytaceae type</i>	Tree	Mrytaceae	Solitary	Mar-May	A
<i>Psidium guajava</i> L.		Tree		Solitary		
<i>Corymbia citriodora</i> (Hook.) K.D.Hill & L.A.S.Johnson		Tree		Panicle of umbel		
<i>Urtica dioica</i> L.	<i>Urtica type</i>	Herb	Urticaceae	Catkin	Feb-May	A
<i>Girardinia diversifolia</i> subsp. Diversifolia		Herb		Catkin		
Broken, ill-defined or distorted	Unidentified	-	-	-	-	-

A =Anemophilous and E = Entemophilous

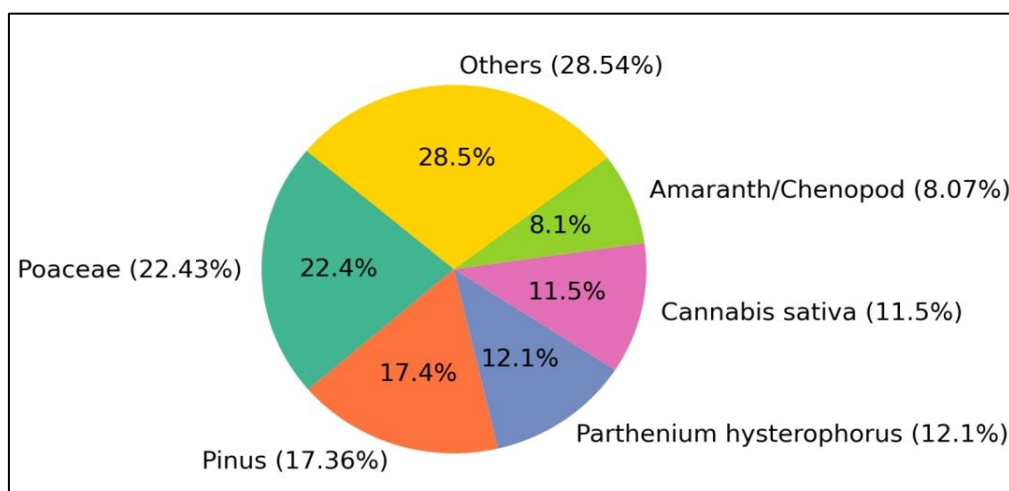


Figure 4. Dominant pollen type in percentage.

Pinus – contributed 17.36%, primarily during spring, associated with chir-pine forests in the valley.

Parthenium hysterophorus – a highly allergenic weed species, contributed 12.1%.

Cannabis sativa – widely occurring in wild and disturbed habitats, contributed 11.5%.

Amaranth/Chenopod types – contributed 8.07%, commonly found in weedy and open areas.

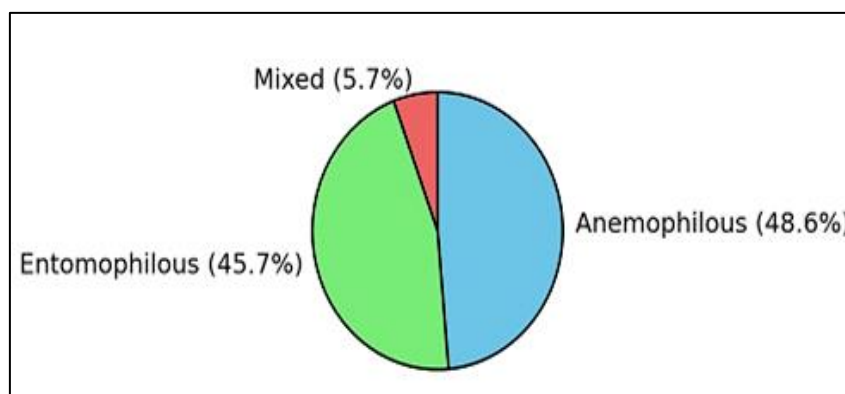


Figure 3. Pollen type in percent.

Other dominant contributors included pollen from *Morus*, *Albizia*, *Syzygium*, and *Holoptelea*, showing a mix of natural, cultivated, and urban vegetation sources.

Seasonal Variation in Pollen Concentration

Spring (March–April): Highest pollen concentration overall. Dominated by pollen from Poaceae (grasses), Pinaceae (pines), and early flowering shrubs like *Artemisia* and

Cupressaceae (cypresses). High temperatures and dry conditions promote massive pollen release. Major allergenic risk season for sensitive individuals.

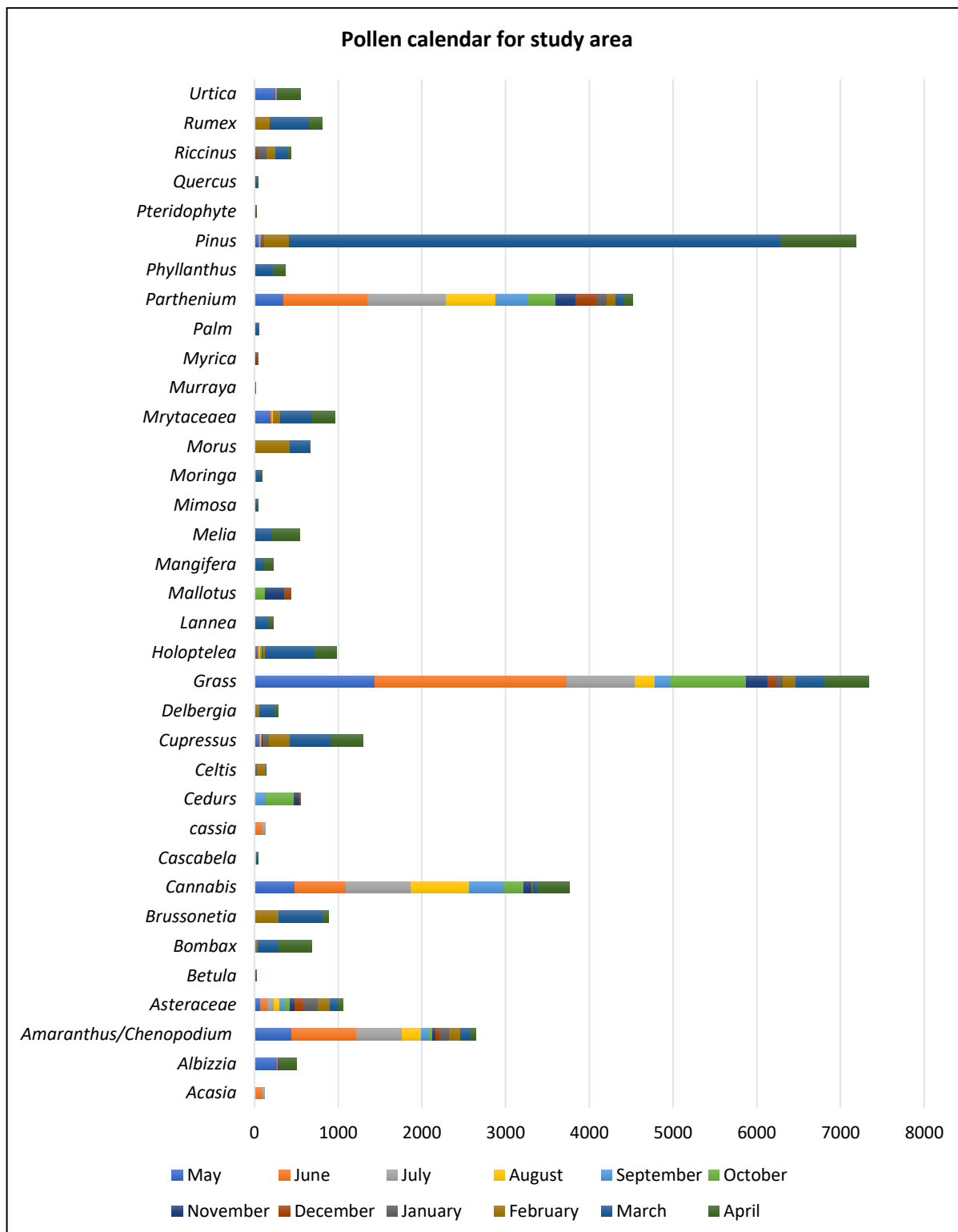


Figure 5. Pollen calendar prepared for study area

Summer (May–June): Continued high pollen load, particularly from grasses (Poaceae) and broadleaf trees. Some species begin fruiting, slightly reducing airborne pollen by late June. Wind speeds are relatively higher, aiding pollen dispersal. Allergy symptoms may persist but slightly reduce compared to spring peak.

Table 2: Seasonal Pollen Activity

Season	Pollen Load	Main Contributors	Allergy Risk
Spring	Very High	Poaceae, Pinaceae, Cupressaceae	Very High
Summer	High	Poaceae, Asteraceae	High
Monsoon	Low	Few grasses, fungal spores rising	Low
Post-Monsoon	Moderate	Asteraceae, Chenopodiaceae	Moderate
Winter	Very Low	Some gymnosperms	Very Low

Monsoon (July–September): Sharp decline in airborne pollen due to heavy rainfall causing wet deposition (pollen is washed out of the air). Air is comparatively cleaner, except for fungal spores which may increase. Low allergenic risk from pollen during this period.

Post-Monsoon (October–November): Moderate resurgence of pollen, especially from late-flowering species like Asteraceae and some weed species. Dry and cooler weather leads to some pollen re-entrainment from ground surfaces. Allergy incidence may slightly rise again, but not as severe as spring.

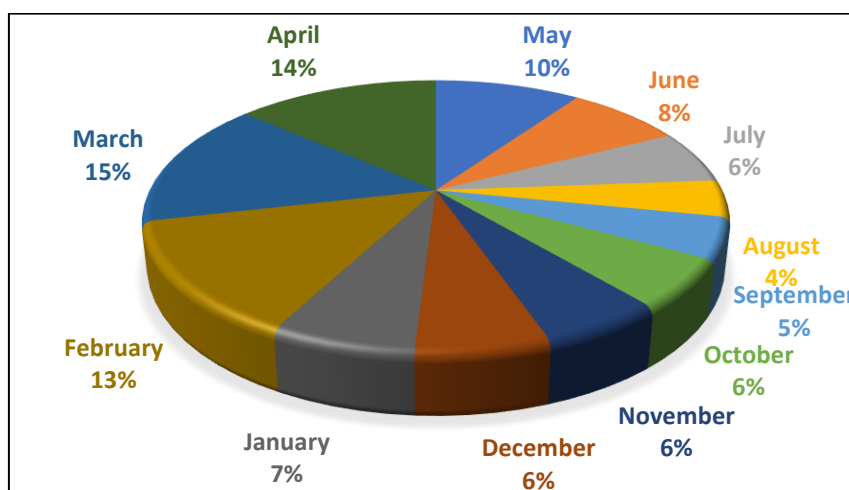


Figure 6. Monthly occurrence of identified Pollen types.

Winter (December–February): Lowest airborne pollen concentrations. Cold temperatures and moisture suppress pollen release. Only a few hardy species (some gymnosperms) release limited pollen. Minimal allergenic threat during this time.

Spring is the dominant pollen season, followed by early summer. Monsoon acts as a natural cleanser of the atmosphere. Post-monsoon brings minor secondary peaks from late-blooming herbs and shrubs. Winter has negligible pollen presence (Table 2, Figure 6).

Effect of Meteorological Parameters

Correlation analysis revealed that temperature had a significant positive relationship with airborne pollen concentrations (Fig.7). Warmer conditions appeared to enhance pollen release and atmospheric persistence. Other meteorological variables, including rainfall, relative humidity, and wind speed, showed non-significant negative correlations with pollen counts. This suggests that rainfall and humidity may suppress airborne pollen by promoting washout or inhibiting dispersal, whereas wind effects were variable and likely influenced by local topography.

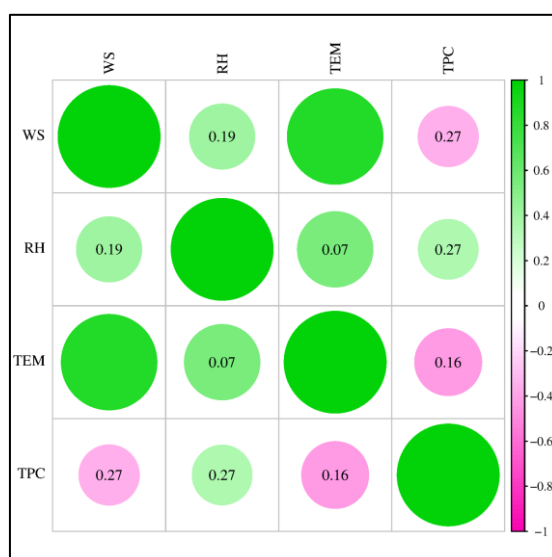


Figure 7: Plot showing Pearson's correlation between meteorological parameters (T = Temperature, H=Humidity, WS=Wind Speed, WD=Wind Direction, RF=Rainfall) and PC=Pollen Count

Fungal Spore Spectrum

In addition to pollen, the study identified 23 fungal spore types from 20 genera, encompassing major groups; Ascomycetes (18 types) dominated the airspora, Basidiomycetes (3 types), Deuteromycetes, and Zygomycetes (1 type each) were also present (Plate 5 & 6). Frequent genera included *Alternaria*, *Aspergillus/Penicillium*, *Cladosporium*, *Curvularia*, and *Fusarium*. Spores were classified based on shape, septation, color, and wall ornamentation. The *Alternaria* type was most dominant, characterized by septate, club-shaped conidia commonly associated with allergic reactions.

Discussion

This study offers a detailed characterization of airborne pollen and fungal spore diversity in the Srinagar Valley of the Garhwal Himalaya, providing critical insights into the aerobiological and environmental dynamics of a mid-altitude subtropical ecosystem. The findings reflect both the intrinsic biodiversity of the region and the complex interactions between vegetation, meteorological variables, and topographic influences.

Pollen Diversity and Sources

The identification of 52 pollen-producing taxa grouped into 35 morphotypes is a testament to the rich vegetative heterogeneity of the valley. This includes natural forests (*Pinus roxburghii*, *Quercus* spp.), cultivated trees (*Dalbergia sissoo*, *Syzygium cumini*), ornamental plants (*Tecoma stans*, *Cupressus torulosa*), and invasive species (*Parthenium hysterophorus*, *Cannabis sativa*). Such diversity is typical of Himalayan foothill environments, where natural and anthropogenic landscapes coexist (Chaurasia et al., 2023; Kumar & Pande, 2021).

Notably, wind-pollinated species like Poaceae, Pinaceae, Cupressaceae, and Amaranthaceae dominated the pollen spectrum, accounting for nearly half (48.6%) of all airborne pollen. This aligns with earlier aerobiological surveys from other Indian valleys such as the Doon Valley and the Kashmir Valley, where grasses and pines have consistently emerged as major pollen sources (Sharma et al., 2020; Bhat et al., 2022; Rajasekar et al., 2021).

Entomophilous pollen types, although less adapted to wind dispersal, were also significantly represented (45.7%), likely due to secondary dispersal by wind, animal movements, or urban disturbances. This phenomenon has been previously documented in semi-urban environments (Mandrioli et al., 1998; Singh et al., 1993), suggesting that pollen from insect-pollinated species can still contribute to allergic burdens, particularly during high flowering seasons.

Dominant Allergenic Taxa

Poaceae emerged as the most dominant contributor (22.43%) to the total pollen count, reaffirming its status as a major global aeroallergen (Damialis et al., 2021). This family includes several allergy-inducing genera such as *Cynodon*, *Apluda*, and *Digitaria*, commonly found in lawns and roadsides throughout the region. The next major contributors, *Pinus* (17.36%) and *Parthenium* (12.1%), are similarly consistent with studies

from the Western Himalayas and Indo-Gangetic Plains (Gautam et al., 2020; Basak et al., 2003; Tiwari et al., 1993).

Parthenium hysterophorus, in particular, poses a significant public health concern. Its highly allergenic pollen is linked to contact dermatitis, asthma, and rhinitis, with increasing prevalence reported across northern India (Singh & Dahiya, 2008; Bhat et al., 2022). *Cannabis sativa*, another dominant type (11.5%), is gaining attention due to its rising prevalence in airborne pollen, particularly in disturbed and waste land areas (Tripathi et al., 2023; Basak et al., 2003).

Seasonal Variability

The seasonal pattern of pollen concentration, peaking in pre-monsoon months and declining during monsoon, is typical of subtropical and temperate Himalayan settings (Mandal et al., 2008; Bhardwaj et al., 2022). The spring peak (March–April) coincides with the anthesis of key taxa like *Pinus roxburghii*, *Holoptelea integrifolia*, and various grasses, exacerbated by dry conditions and increasing temperatures that facilitate pollen release (Schappi et al., 1998; Almeida et al., 2018).

Monsoon rains (July–September) significantly reduced airborne pollen through wet deposition, supporting findings from comparable studies in northeast and southern India (Nair et al., 1986; Piotrowska & Kaszewski, 2011). Post-monsoon resurgence (October–November) and a winter lull (December–February) further reinforce the role of temperature and humidity in modulating airborne pollen dynamics (Gioulekas et al., 2004; Kumar et al., 2024).

Fungal Spore Dynamics

The detection of 23 fungal spore types across 20 genera highlights the valley's aerobiological complexity. Dominant genera *Alternaria*, *Cladosporium*, and *Curvularia* are among the most common atmospheric fungi and significant sources of aeroallergens globally (Lacey & West, 2006; Arora & Jain, 2008; Zhang et al., 2021). *Alternaria*, in particular, is associated with late summer and autumn peaks and has been implicated in severe asthma cases (WHO, 2022; Sharma et al., 2011).

The presence of Basidiomycetes and Zygomycetes, though less abundant, suggests that fungal spores contribute consistently to background aeroallergen levels, particularly during moist monsoon periods (Mandal et al., 2008; Kumar et al., 2024).

Influence of Meteorological Variables

Temperature exhibited a significant positive correlation with pollen concentrations, echoing patterns from multiple international studies (Feng et al., 2019; Bharti et al., 2023; Almeida et al., 2018). Higher temperatures promote anther dehiscence and increase pollen longevity in the air, explaining elevated counts during warm, dry seasons.

Conversely, rainfall, humidity, and wind speed were negatively correlated, though not significantly. Rainfall facilitates wet deposition, humidity induces pollen aggregation, and variable wind dynamics especially in mountainous terrains modulate dispersal patterns (Gioulekas et al., 2004; Tripathi et al., 2023; Kumar et al., 2024).

Conclusion

This study provides baseline data for future allergological forecasting and biodiversity monitoring in mid-Himalayan regions. With increasing urbanization, land-use changes, and climate variability, the dynamics of airborne biological particles in such ecotones are expected to become more complex. Continued aerobiological surveillance is crucial for mitigating allergic diseases and informing urban planning and public health policies.

Implications for Public Health and Future Research

The dominance of allergenic species such as *Parthenium hysterophorus* and *Cannabis sativa*, coupled with their sensitivity to climatic variables, highlights the potential for increased allergic reactions in the population amidst changing climate conditions. The observed trends necessitate the development of region-specific pollen calendars and early warning systems to mitigate health risks. Furthermore, integrating long-term aerobiological data with climate models could enhance our understanding of future shifts in pollen distribution and allergenicity, aiding in public health planning and biodiversity conservation efforts.

Authors Contribution:

Conceptualization, Prabhawati Tiwari and Alok Gautam; methodology, S Prabhawati Tiwari, Alok Gautam; software Ajendra Singh Bagri and Shikha Arya; data curation, Shikha Arya and Ajendra Singh Bagri; writing- original draft preparation, Ajendra Singh Bagri and Shikha Arya; writing- review and editing, Ajendra Singh Bagri and Shikha Arya; visualization, Prabhawati Tiwari and Alok Gautam ; supervision, Prabhawati Tiwari; funding acquisition, Shikha Arya. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Not Applicable

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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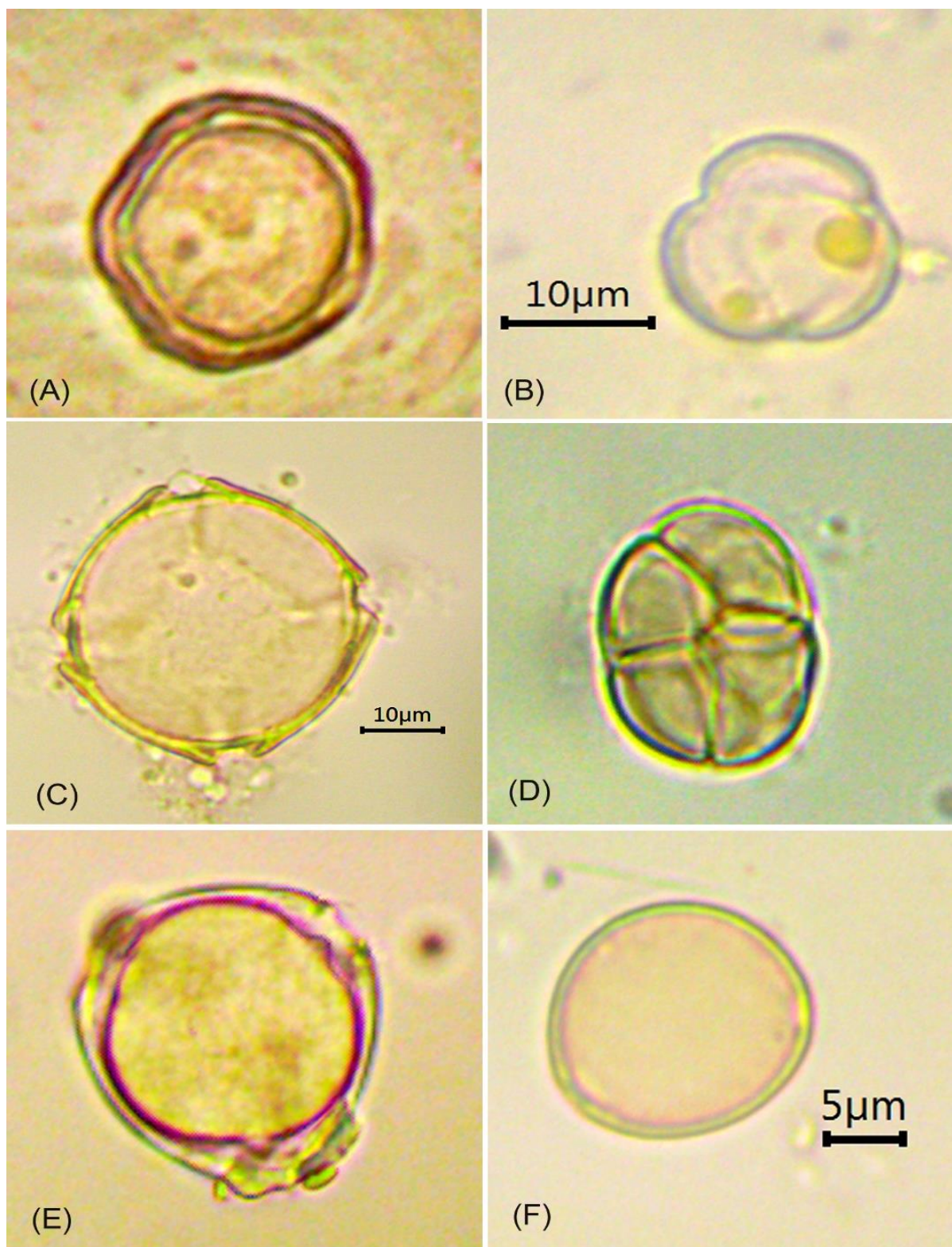


Plate 1: LM photographs of pollen grains (A) *Holoptelea integrifolia* (1000X) (B) *Mangifera indica* (1000X) (C) *Melia azadirach* (1000X) (D) *Mimosa* Sp. (1000X) (E) *Moringa oleifera* (1000X) (F) *Morus alba* (1000X)

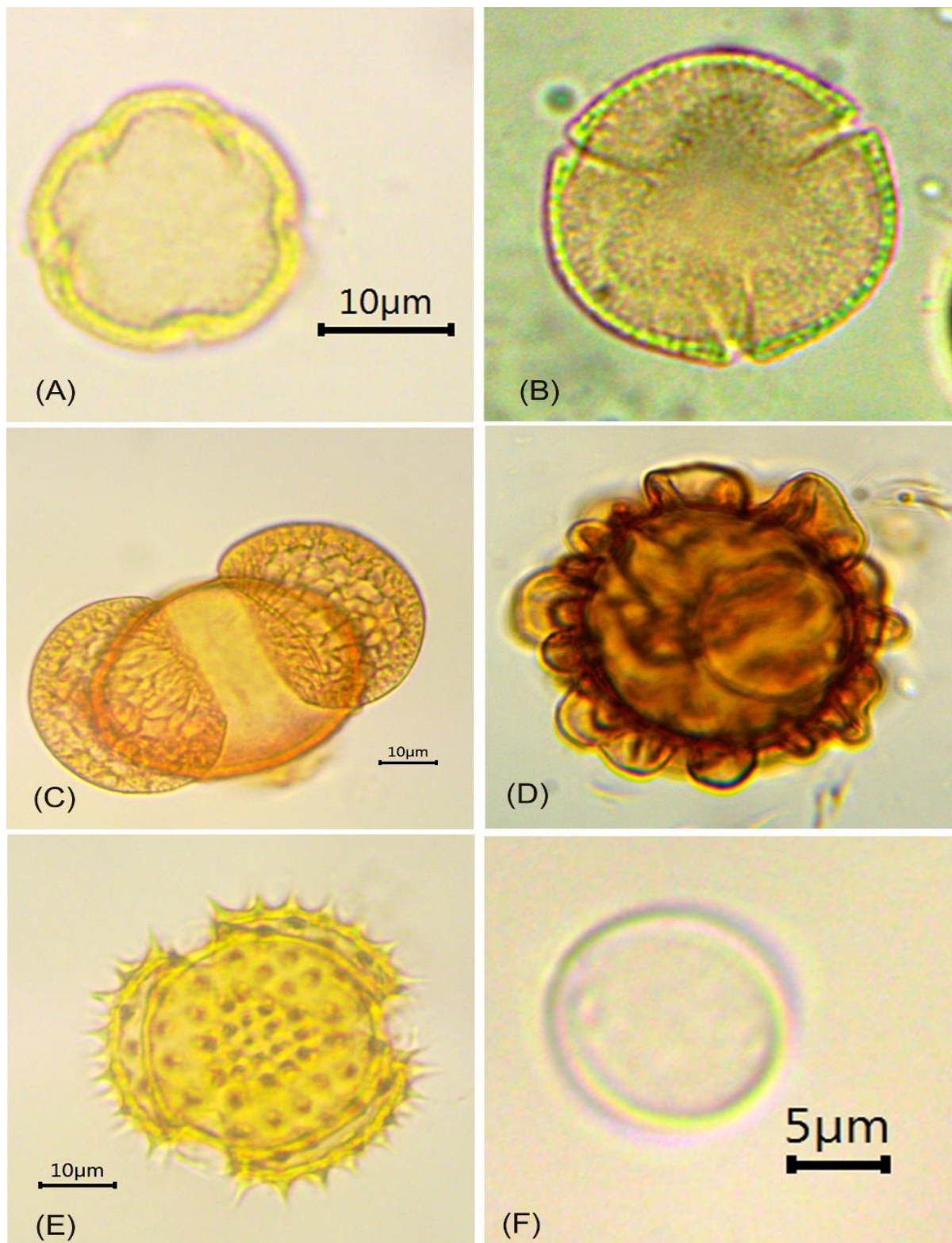


Plate 2: LM photographs of pollen grains (A) *Phyllanthus emblica* (1000X) (B) *Rumex hastatus* (1000X) (C) *Pinus roxburghii* (400X) (D) Pteridophyte (1000X) (E) *Tegetas* sp. (1000X) (F) *Urtica dioica* (1000X)

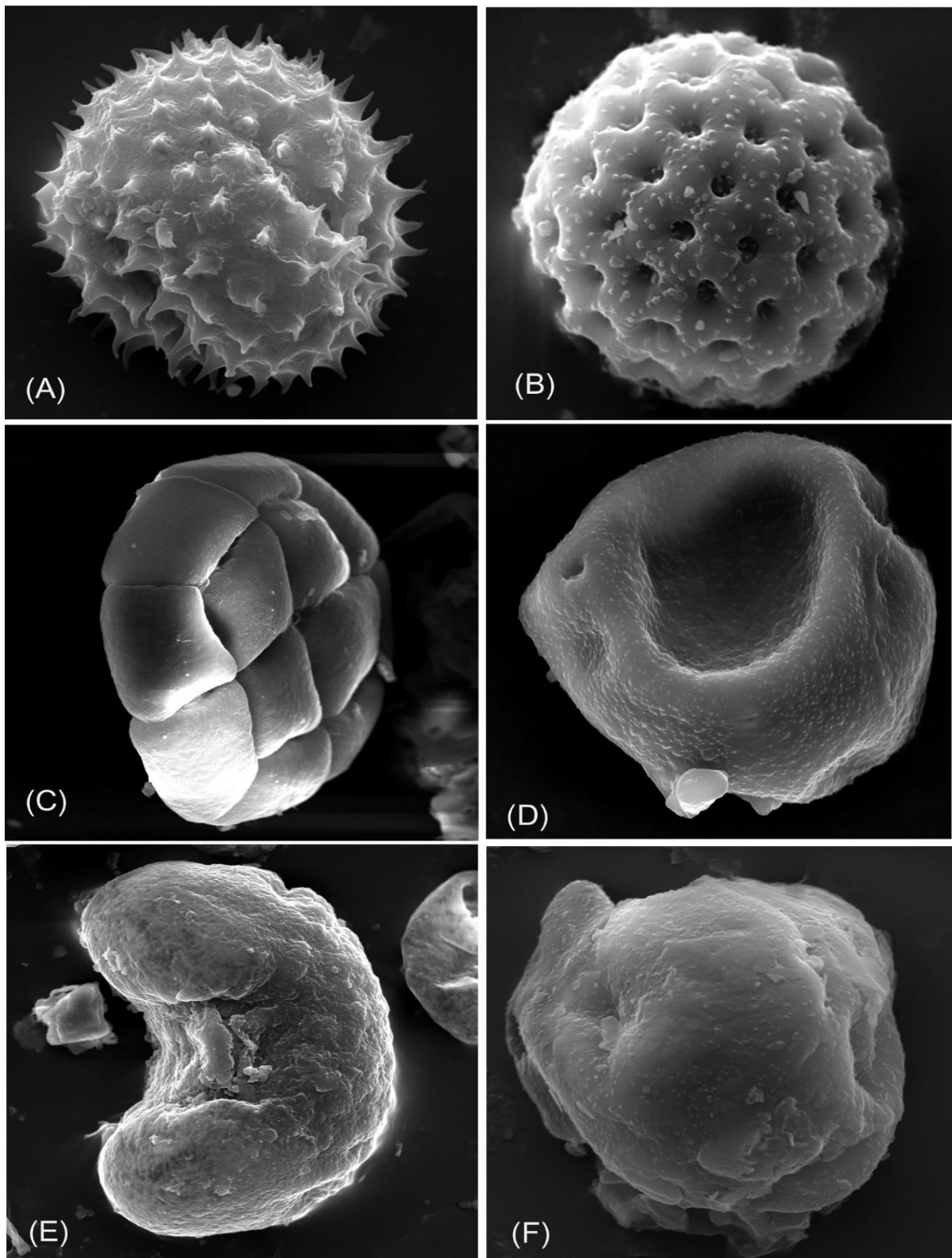


Plate 3: SEM photographs of pollen grains (A) *Tagetes sp.*, (B) *Amaranthus sp.*, (C) *Albizia lebbeck*, (D) *Cannabis sativa*, (E) *Cedrus deodara* (F) *Celtis australis*

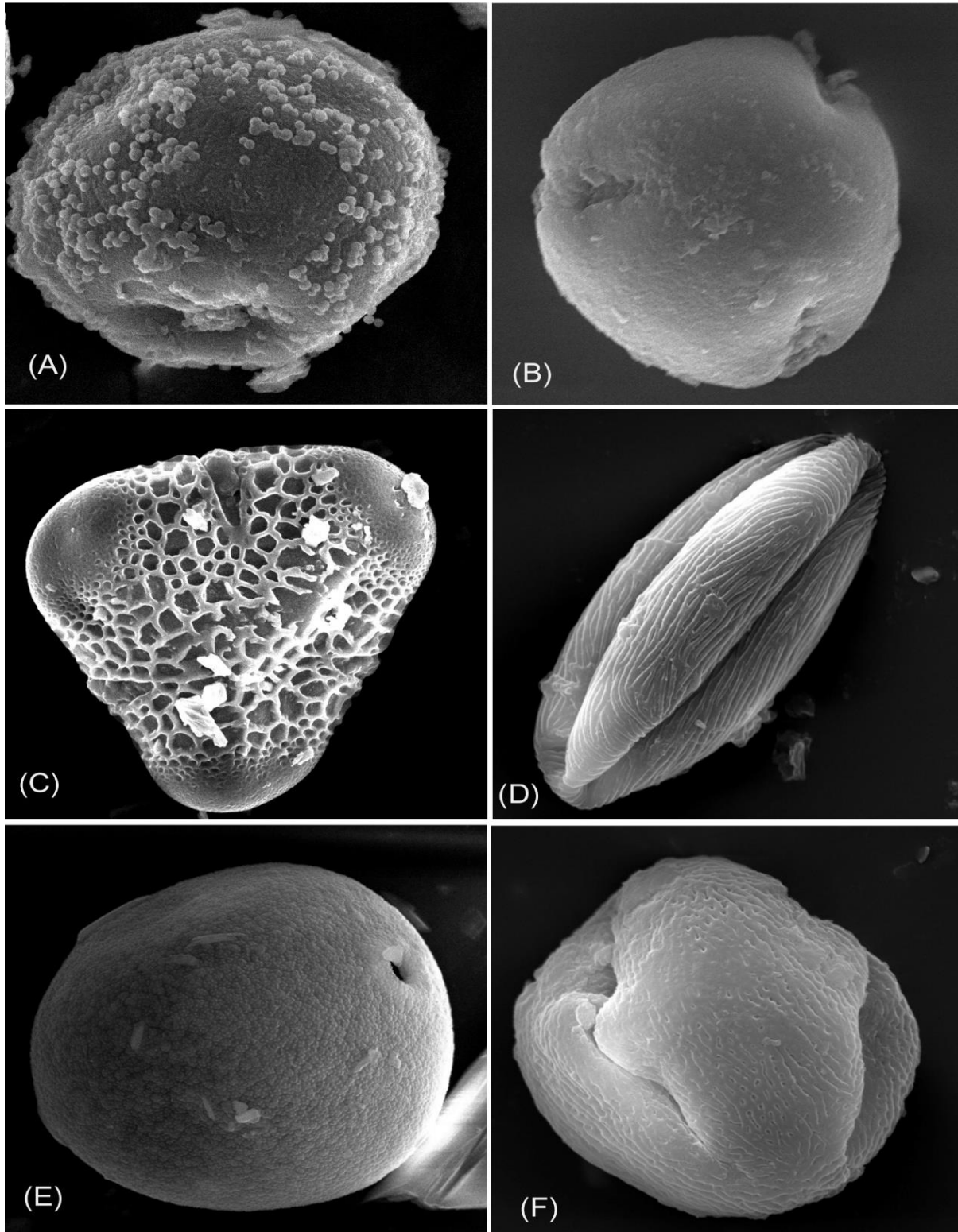


Plate 4: SEM photographs of pollen grains- (A) *Cupressus torulosa*, (B) *Dalbergia sissoo*, (C) *Bombax ceiba*, (D) *Lannea coromendalica*, and (E) *Grass*, (F) *Mangifera indica*

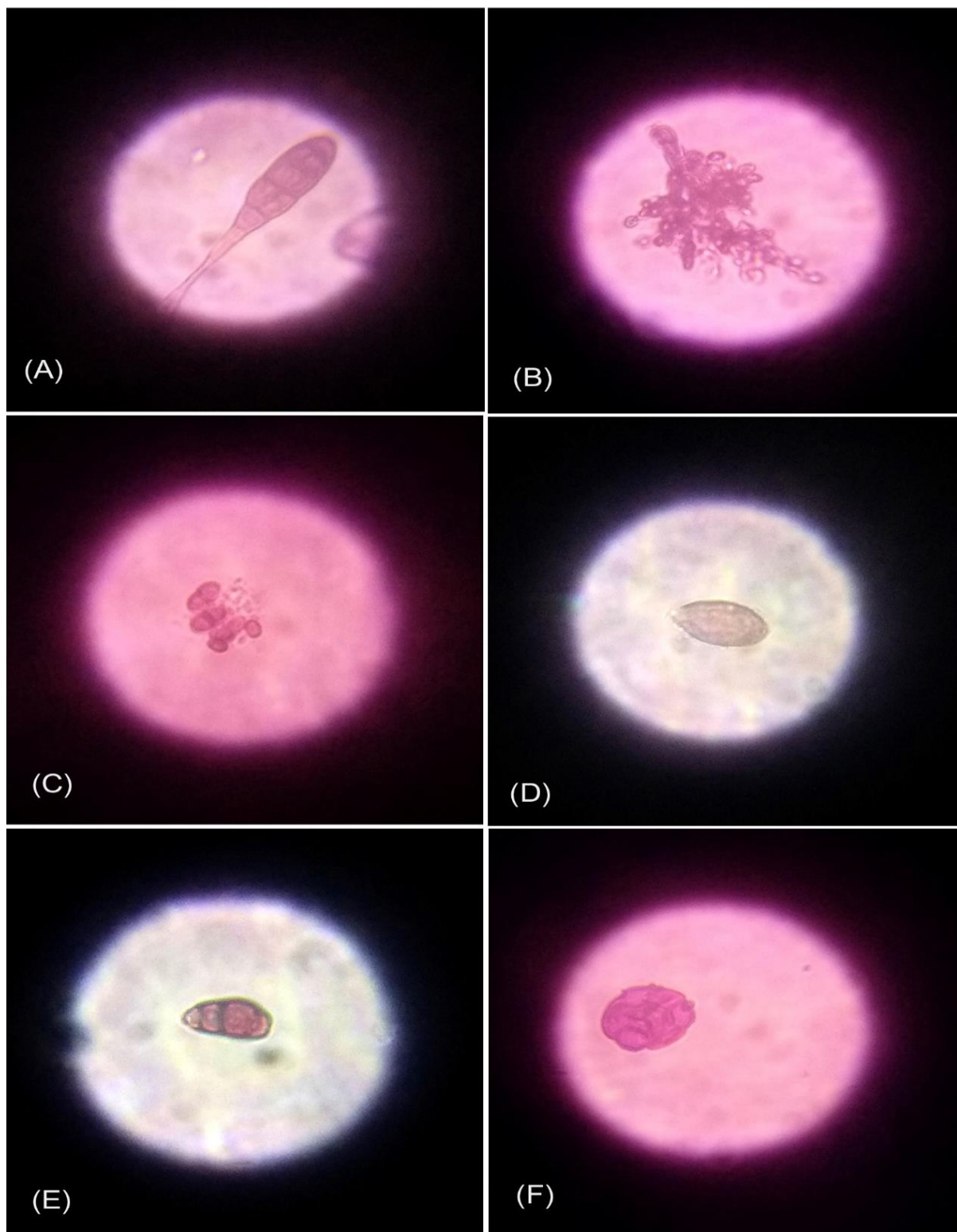


Plate 5: LM photographs of fungal spore types- (A) *Alternaria*, (B) *Aspergillus/Penicillium*, (C) *Bipolaris*, (D) *Chaetomium*, (E) *Curvularia*, (F) *Epicoccum*.

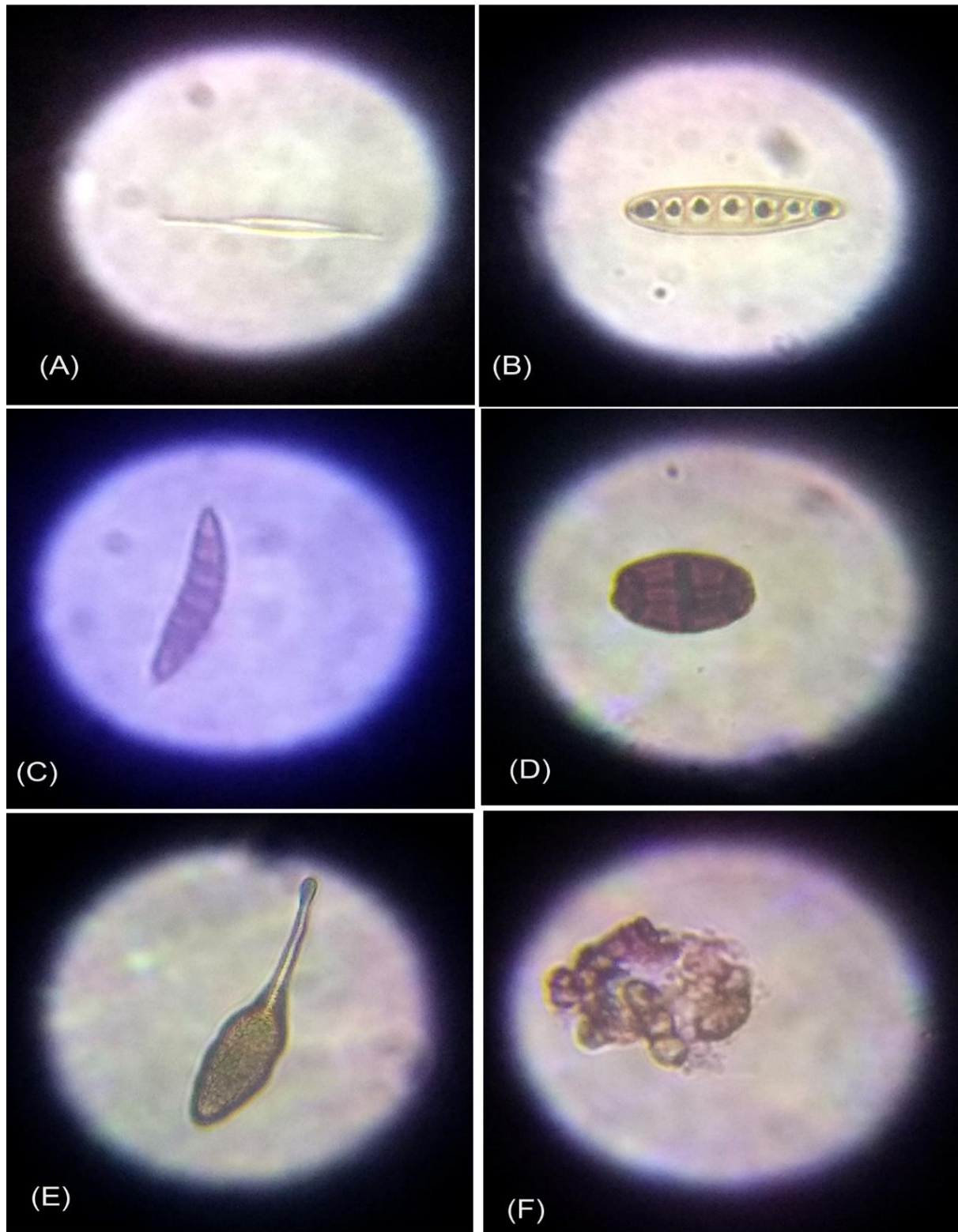


Plate 6: LM photographs of fungal spore types- (A) *Furasium*, (B) *Helminthosporium/Drechslera*, (C) *Leptosphaeria*, (D) *Pithomyces*, (E) *Puccinia*, (F) *Torula*.