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POLLEN MORPHOLOGY OF SOME PLANT SPECIES FROM TERMEZ, UZBEKISTAN: SEM ANALYSIS AND IMPLICATIONS FOR AEROPALYNOLOGICAL MONITORING AND ENVIRONMENTAL MANAGEMENT

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ABSTRACT

This study presents the first high-resolution SEM characterization of pollen from ten ecologically dominant, aerobiologically important plant species in Termez, southern Uzbekistan. These species are abundant across the region, common in urban and suburban settings, and likely add to airborne pollen loads. Between March and October 2024, we collected 30 mature pollen grains per species and analyzed them with a JEOL JSM-IT210 SEM. One-way ANOVA revealed big interspecific differences in polar and equatorial diameters ($P<0.001$); polar diameters ranged from 14.89 to 112.67 µm. Most taxa had oblate to oblate-spheroidal shapes ($P/E < 1.0$). Principal component analysis (PCA) showed that the first two components captured 99.98% of the total variance, clearly separating species by size and shape. Distinct exine ornamentation patterns also aided species-level identification. These results set a critical baseline for the Pollen Atlas of Uzbekistan and have practical applications: improving allergy forecasts by enabling precise airborne pollen monitoring and guiding evidence-based urban planning and environmental management in arid Central Asia.

Keywords: Pollen morphology, SEM, Aeropalynology, Environmental monitoring, Morphometry, PCA, Pollen atlas, Termez, Uzbekistan, Ecological management.

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1. INTRODUCTION

Pollen grains—the male gametophytes of seed plants—serve two key roles in terrestrial ecosystems: they enable genetic exchange through pollination and form part of biological aeroplankton. Among angiosperms, these tiny structures show remarkable morphological diversity, from less than 5 µm in some micro-pollen to over 200 µm in specialized families. Their complex features—size, shape, symmetry, aperture types, and intricate exine layers—arise from the interplay of genetics and local environmental pressures. These factors influence pollen viability, water uptake, and long-distance dispersal. So, ultrastructural traits remain evolutionarily conserved, making them valuable for plant systematics, phylogenetics, and evolutionary biology (Erdtman, 1952; Park & Song, 2010; Attique et al., 2022; El Ghazali, 2025). Long-term aerobiological studies demonstrate that pollen-season characteristics can respond measurably to climatic variation, including changes in pollen-season timing, duration, and intensity (Adams-Groom et al., 2022; López-Orozco et al., 2021; Piotrowska-Weryszko et al., 2021). In particular, long-term observations of *Quercus* pollen in southern Spain revealed changes in both pollen-season length and intensity associated with climatic fluctuations (López-Orozco et al., 2021). Similarly, studies of major allergenic pollen types in the United Kingdom have demonstrated the value of regional pollen calendars and seasonal statistics for characterizing airborne pollen exposure (Adams-Groom et al., 2020). Over the last twenty years, palynology has become essential for resolving taxonomic issues, identifying cryptic species, and tracking vegetation responses to climate change (Damialis et al., 2021; Javed et al., 2024). To capture fine structural

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details, the field has shifted from standard light microscopy (LM) to high-resolution techniques. LM still works for routine pollen monitoring but lacks the resolution to see sub-micron surface features. Scanning electron microscopy (SEM) is now the go-to method for detailed studies, offering exceptional clarity on tectum perforations, supratectal elements, and complex exine patterns (Guimarães et al., 2018; Patrício et al., 2024; Atazadeh & Ghahremaninejad, 2025). High-resolution SEM data have strengthened aerobiological works by enabling comprehensive regional pollen atlases. These references are crucial for forensic palynology, melissopalynology, paleoecology, and environmental monitoring (Meng et al., 2024; Van Haeften et al., 2024; Makhkamov et al., 2025). Recent global research underscores the growing need for such detailed datasets, especially as climate change shifts vegetation, extends flowering seasons and alters pollen production and dispersal. Reliable species-level identification of airborne pollen directly impacts public health—atmospheric pollen triggers type I hypersensitivity, worsening seasonal allergies and asthma in cities (D'Amato et al., 2020). Automated pollen monitoring systems that use machine learning and deep neural networks rely heavily on high-quality reference morphological data (Suanno et al., 2021; Oteros et al., 2022). Recent SEM research has demonstrated that detailed examination of pollen size, morphology, and stratified exine sculpture can reveal interspecific differences and contribute to taxonomic characterization (Alhomaidi, 2024; Akhmedov et al., 2025). Without robust SEM-based references, these systems often fail to distinguish among similar, co-flowering, and cross-reactive species. Despite the known value of micro-morphological and morphometric data, major research gaps exist in Central Asia, especially Uzbekistan. The arid and semi-arid landscapes there support a specialized flora of xerophytic, halophytic, and ephemeral species (Tojibaev et al., 2016). Long-term studies from North America have shown that anthropogenic climate change has been associated with earlier and longer pollen seasons and increased pollen concentrations (Anderegg et al., 2021). Comparable evidence from Europe, Australia, and Japan indicates that climatic variation can influence pollen-season characteristics and allergenic airborne pollen dynamics (Kishikawa & Koto, 2021; López-Orozco et al., 2021; Adams-Groom et al., 2022; Davies et al., 2022). The Surkhandarya Region in southern Uzbekistan, along the Amu Darya River valley, exemplifies these harsh conditions: intense heat, low rainfall, high dust, and extreme aridity. But systematic high-resolution palynology here is scarce. Earlier studies near Samarkand provided useful preliminary data on airborne pollen and allergenic flora, primarily using light microscopy (Jumayeva et al., 2024; Djumayeva et al., 2024; Fayzullaeva et al., 2025). The clinical relevance of airborne pollen is further highlighted by research on thunderstorm asthma, in which environmental and meteorological conditions interact with aeroallergen exposure and susceptible populations (Thien et al., 2025; Aytbayeva et al., 2026). Recent work has begun using SEM for some taxa, such as Nepeta species (Nozimova et al., 2024, 2025; Makhkamov et al., 2025). Yet these studies remain limited in scope, largely descriptive, and lack comprehensive morphometric analysis with multivariate statistics. This lack of ultrastructural data limits local authorities from developing accurate pollen calendars, managing allergies, monitoring biodiversity changes from desertification and climate change, and evaluating long-range pollen and dust transport across Central Asian corridors (Noroozi et al., 2022). The development of detailed morphological reference datasets is therefore particularly important for improving the interpretation of airborne pollen assemblages, as demonstrated by recent multi-year metabarcoding research showing substantial diversity and complexity within airborne pollen communities (Campbell et al., 2023; Rakhmonov et al., 2026). Merging SEM-derived morphometric and sculptural data with aerobiological monitoring is especially vital in arid environments, where pollen morphology directly affects dispersal, desiccation resistance and allergenicity under extreme conditions. Recent international studies show that combining SEM with multivariate techniques such as PCA clarifies taxonomic boundaries and links pollen traits to environmental adaptation (Qu et al., 2025; Şeker, 2025; Rakhmonov et al., 2025; Mustanov et al., 2026). Still, such integrated high-resolution approaches haven't been applied to the unique flora of southern Uzbekistan. To address this gap, we provide the first detailed SEM-based morphometric and exine ornamentation analysis of ten ecologically dominant and aerobiologically important species from Termez. We hypothesize that combining precise morphometric parameters (polar diameter, equatorial diameter, P/E ratio) with high-resolution SEM of exine sculpture will yield robust, species-specific diagnostic profiles. These should overcome morphological convergence common among hyper-arid adapted taxa and offer reliable criteria for species identification in taxonomy and aerobiology.

Here is a more scientifically refined and publication-ready version suitable for a high-impact journal:

The specific objectives of this study were to:

1. Systematically characterize the pollen morphology of the target taxa by measuring polar diameter (PD), equatorial diameter (ED), P/E ratio, aperture characteristics and ultrastructural exine ornamentation using standardized scanning electron microscopy (SEM) protocols.
2. Apply multivariate statistical analyses, particularly Principal Component Analysis (PCA), to quantify interspecific morphological variation, identify the key traits contributing to phenotypic divergence and elucidate

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taxonomic relationships among the investigated taxa.
3. Establish a comprehensive, high-resolution palynological reference dataset to support the development of the national *Pollen Atlas of Uzbekistan* and provide a scientific foundation for applications in clinical allergology, sustainable urban greening, aerobiological monitoring, biodiversity assessment, and ecological forecasting in the arid and semi-arid ecosystems of Central Asia.

2. MATERIALS AND METHODS

2.1. Study Area and Climatic Conditions

The study was conducted in Termez (37°13′N, 67°17′E), the administrative center of the Surkhandarya Region in southern Uzbekistan (Fig. 1).

The area is characterized by an extremely arid continental climate with hot, dry summers and relatively mild winters, influenced by its location in the Amu Darya River valley. Pollen sampling was performed during the main flowering period from March to October 2024. During this period, mean monthly air temperatures ranged from 12.6°C in March to 19.1°C in October, while average relative humidity gradually decreased from 64% to 61% (Fayzullaeva et al., 2025). These conditions are typical for the hyper-arid climate of southern Uzbekistan and directly affect anther dehiscence, pollen release, and atmospheric dispersal. Wind speeds during the sampling season ranged between 18 and 24 m/s. The local vegetation is dominated by xerophytic and halophytic species, with scattered urban green areas, making Termez a representative site for aeropalynological research in arid zones.

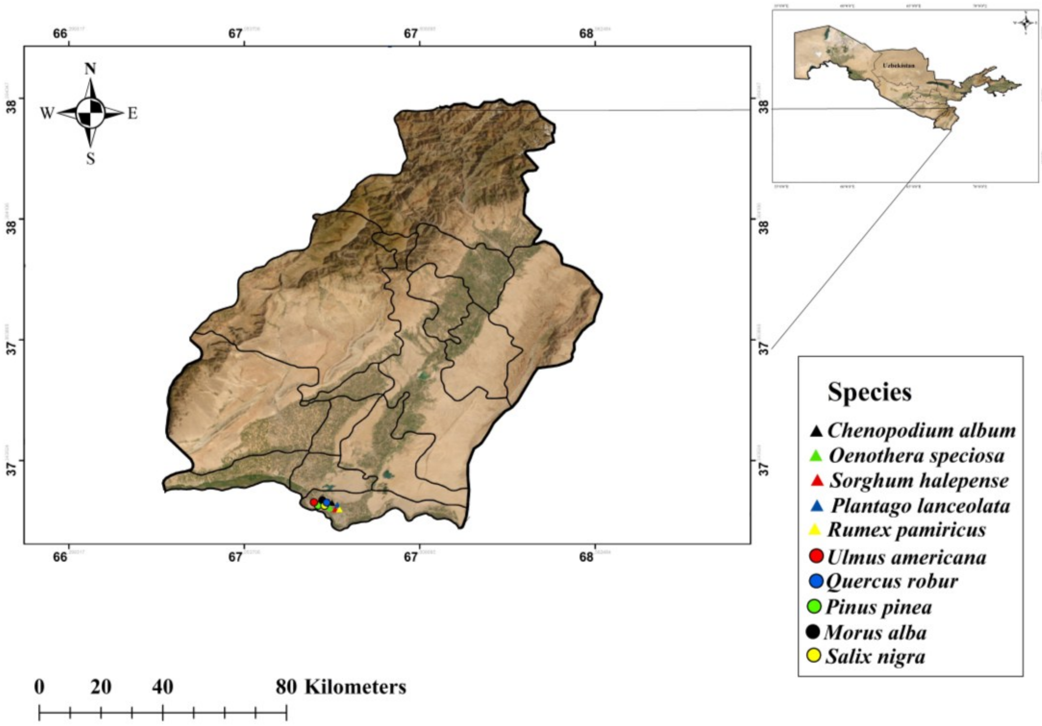

Fig. 1: Map showing the location of Termez in the Surkhandarya Region, southern Uzbekistan, and the collection sites of the ten studied plant species.

2.2. Sampling Design and Specimen Collection

Between March and October 2024, we systematically collected mature floral buds from urban and peri-urban habitats across Termez. To get representative geographic and ecological coverage, we used a stratified random sampling design (Rakhimova et al., 2021). For each of the ten plant species, we harvested mature unopened anthers from at least five distinct individuals—these served as biological replicates. We kept a minimum of 50 meters between selected plants to avoid sampling genetically identical clones. Plant identification was double-checked using the World Flora Online database (Norkulova et al., 2024, 2025; Nozimova et al., 2025). We prepared voucher specimens and deposited them in the Palynology Laboratory at the Institute of Biochemistry, Samarkand State University. Samples were placed in aerated paper bags and transported to the lab under controlled conditions.

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2.3. Pollen Preparation and Scanning Electron Microscopy (SEM)

We extracted pollen grains from anthers and subjected them to standard acid acetolysis (Erdtman, 1952) to remove cytoplasmic contents. Samples were fixed in 2.5% glutaraldehyde, rinsed with phosphate-buffered saline (PBS, pH 7.4) and dehydrated through a graded ethanol series (30%, 50%, 70%, 90%, and 100%). To preserve three-dimensional structure, specimens were dried using a CO_2 critical-point dryer (Santos & Ledru, 2022). Dried pollen was mounted on aluminum stubs with double-sided carbon adhesive tape and sputter-coated with gold. We observed and imaged the samples using a JEOL JSM-IT210 scanning electron microscope at an accelerating voltage of 2–5 kV. Low-magnification images (1,000–2,000×) were used for morphometric measurements, while high-magnification images (8,000–18,000×) captured detailed exine sculpture and aperture analysis. Pollen size classes were assigned according to Erdtman's scale (Meng et al., 2024).

2.4. Morphometric Measurements and Statistical Analysis

For each species, we randomly selected 30 fully developed, undamaged pollen grains—6 grains per biological replicate from 5 individuals—for measurement. This sample size gave us enough statistical power and satisfied parametric test assumptions via the Central Limit Theorem. We measured polar diameter (PD), equatorial diameter (ED), and calculated the P/E ratio (Usma et al., 2022; Jumayeva et al., 2024). We also recorded qualitative characters like aperture type and exine ornamentation. Data normality was checked with the Shapiro-Wilk test, and homogeneity of variances with Levene's test (Wrońska-Pilarek et al., 2022; Zhou et al., 2023). For all morphometric variables, we calculated descriptive statistics (mean, standard deviation, minimum, maximum). To explore overall morphological variation and identify key discriminating traits, we performed principal component analysis (PCA) on the correlation matrix of standardized variables (PD, ED, P/E ratio). All statistical analyses and visualizations were done in R software (version 4.3.2) using the factoextra and ggplot2 packages (Wickham, 2016; Kassambara & Mundt, 2020).

3. RESULTS

Scanning electron microscopy (SEM) analysis revealed highly significant quantitative and qualitative variations in pollen morphology among the ten plant species from Termez, Uzbekistan. One-way ANOVA confirmed highly significant interspecific differences for polar diameter (PD; F = 142.6, $P<0.001$) and equatorial diameter (ED; F = 168.3, $P<0.001$). Tukey's HSD post hoc test was performed separately for each variable. The smallest pollen grains were recorded in Salix nigra (PD = 14.89 ± 0.96 µm), while *Oenothera speciosa* produced the largest palynomorphs (PD = 112.67 ± 2.13 µm, ED = 126.67 ± 1.85 µm). Most species exhibited oblate to oblate-spheroidal shapes, as indicated by P/E ratios below 1.0. One-way ANOVA confirmed highly significant differences among the species for both polar and equatorial diameters ($P<0.001$). The P/E ratio ranged from 0.457 (*Quercus robur*) to 0.960 (*Plantago lanceolata*), reflecting a predominance of oblate and oblate-spheroidal pollen morphologies (Fig. 2).

3.1. Statistical Clustering and Variation Mapping

To explore the multidimensional structure of pollen morphological variation, Principal Component Analysis (PCA) was performed on the standardized morphometric variables (polar diameter, equatorial diameter, and P/E ratio). The first two principal components accounted for 99.98% of the total variance (PC1 = 84.15%, PC2 = 15.83%). Factor loadings and eigenvalues are presented in Table 1.

PC1 was predominantly associated with pollen size (high positive loadings for PD and ED), while PC2 was strongly related to pollen shape (high loading for the P/E ratio). The ordination clearly separated *Oenothera speciosa* as an extreme outlier along PC1 due to its large size, and *Quercus robur* along PC2 due to its strongly oblate morphology.

Table 1: Eigenvalues and factor loadings for the first two principal components (PC1 and PC2) based on pollen traits

Morphometric Variable	Principal Component 1 (PC1)	Principal Component 2 (PC2)
Polar Diameter (PD)	0.984	0.122
Equatorial Diameter (ED)	0.991	-0.098
P/E Geometrical Ratio	0.145	0.976
Eigen value	2.524	0.475
Explained Variance (%)	84.15	15.83
Cumulative Variance (%)	84.15	99.98

3.2. *Ulmus americana* (Ulmaceae)

The pollen grains are monads, small, isopolar to heteropolar, and triporate. Polar diameter is 18.48 ± 1.42

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µm, equatorial diameter is 20.99 ± 1.67 µm, with a P/E ratio of 0.880 (oblate-spheroidal). In polar view, the outline is circular to subcircular. Dry grains frequently exhibit sunken pores. The exine is tectate to finely sculptured (Fig. 3.1a).

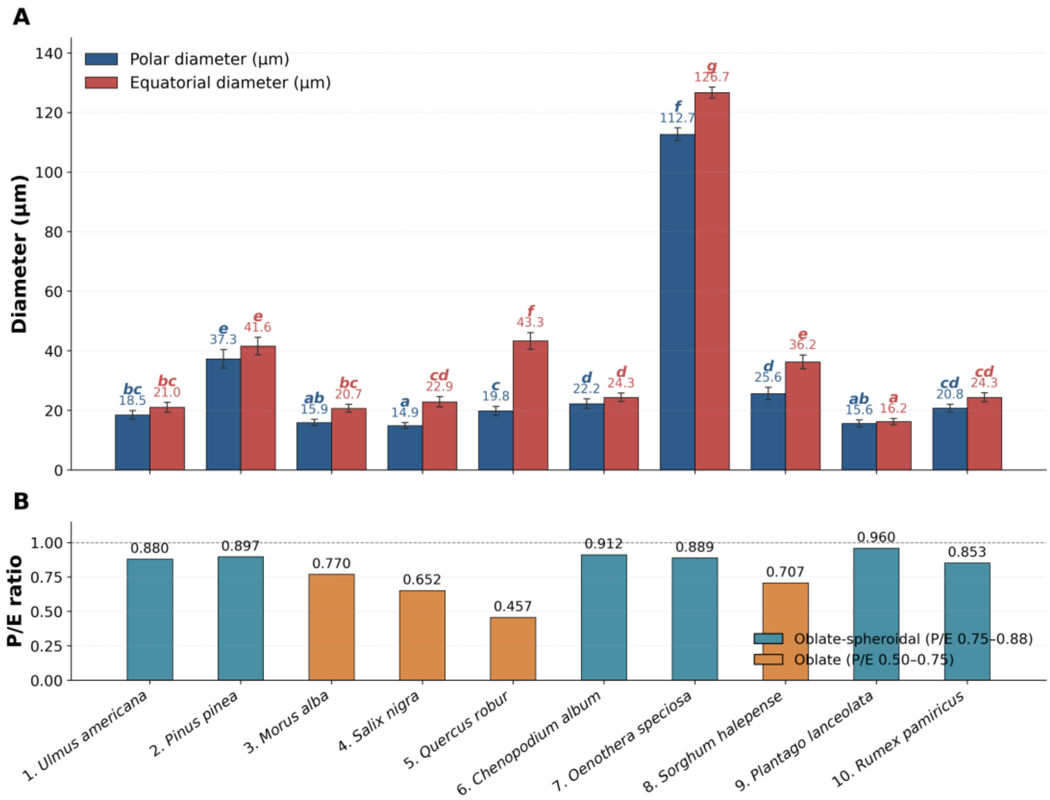

Fig. 2: Quantitative morphometric variation in pollen grains from Termez, Uzbekistan. Polar (PD) and equatorial (ED) diameters (mean ± SD, n = 30 per species). Different letters indicate significant differences within each parameter (Tukey's HSD, P<0.05). Distribution of P/E ratios and corresponding pollen shape classes according to Erdtman's classification.

3.3. *Pinus pinea* (Pinaceae)

The pollen grains are monads and distinctly bisaccate. Polar diameter of the corpus is 37.29 ± 3.12 µm, equatorial diameter is 41.57 ± 2.94 µm, with a P/E ratio of 0.897 (oblate-spheroidal). Overall grain size, including sacci, is considerably larger. In polar view, the corpus outline is circular to elliptical. When dry, the pollen assumes a characteristic boat-shaped form. The exine on the sacci is reticulate, while the corpus is psilate to regulate (Fig. 3.1b).

3.4. *Morus alba* (Moraceae)

The pollen of Morus alba is a monad. The grains are small, isopolar, and porate (mainly triporate). Polar diameter is 15.91 ± 1.05 µm, equatorial diameter is 20.67 ± 1.33 µm, with a P/E ratio of 1.487 (prolate). In polar view, the outline is elliptic. The longest equatorial diameter measures 20.67 ± 1.33 µm. The exine is tectate and psilate to finely scabrate. Dry grains often appear infolded (Fig. 3.1c).

3.5. *Salix nigra* (Salicaceae)

The pollen grains are monads, small, isopolar to slightly heteropolar, and tricolpate to tricolporate. Polar diameter is 14.89 ± 0.96 µm, equatorial diameter is 22.85 ± 1.72 µm, with a P/E ratio of 0.652 (oblate). In polar view, the outline is elliptic. The longest equatorial diameter measures 22.85 ± 1.72 µm. The exine is reticulate. Dry grains show sunken colpi (Fig. 3. 1d).

3.6. *Quercus robur* (Fagaceae)

The pollen grains are monads, medium to large, isopolar, and tricolporate. Polar diameter is 19.78 ± 1.54 µm,

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equatorial diameter is 43.30 ± 2.81 µm, with a P/E ratio of 0.457 (oblate). In polar view, the outline is distinctly elliptic. When dry, the grains become more elongated with sunken apertures. The exine is tectate and scabrate to verrucate (Fig. 3. 1e).

3.7. *Chenopodium album* (Amaranthaceae)

The pollen grains are monads, medium-sized, isopolar, spheroidal, and periporate. Polar diameter is 22.20 ± 1.68 µm, equatorial diameter is 24.34 ± 1.45 µm, with a P/E ratio of 0.912 (oblate-spheroidal). In polar view, the outline is circular. The longest equatorial diameter measures 24.34 ± 1.45 µm. The exine shows microechinate to punctate ornamentation. Dry pollen grains are often irregularly in folded (Fig. 3. 1f).

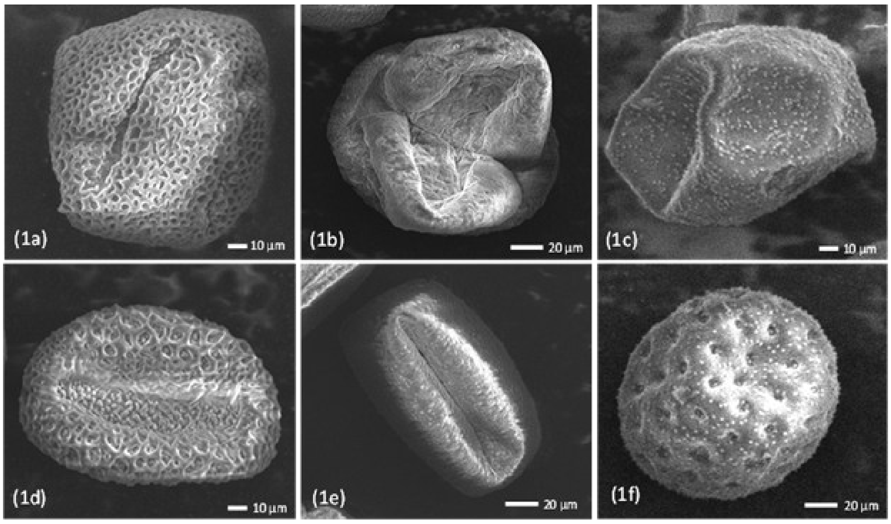

Fig. 3: Scanning Electron Microscopy (SEM) image of pollen from selected plant species [*Ulmus americana* (1a), *Pinus pinea* (1b), *Morus alba* (1c), *Salix nigra* (1d), *Quercus robur* (1e), *Chenopodium album* (1f)].

3.8. *Oenothera speciosa* (Onagraceae)

The pollen grains are monads, large, heteropolar, and porate. Polar diameter is 112.67 ± 2.13 µm, equatorial diameter is 126.67 ± 1.85 µm, with a P/E ratio of 0.889 (oblate-spheroidal). In polar view, the outline is circular to triangular. The longest equatorial diameter measures 126.67 ± 1.85 µm. When dry, the grains often appear boat-shaped or infolded with sunken apertures and are frequently connected by viscin threads. Exine ornamentation is psilate to finely scabrate under light microscopy and micro-reticulate to verrucate under SEM (Fig. 4.1g).

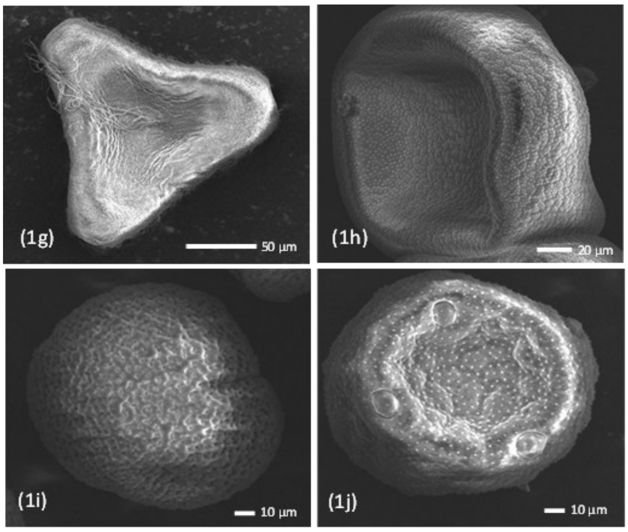

Fig. 4: Scanning Electron Microscopy (SEM) image of pollen from selected plant species [*Oenothera speciosa* (1g), *Sorghum halepense* (1h), *Rumex pamiricus* (1i), *Plantago lanceolata* (1j)].

3.9. *Sorghum halepense* (Poaceae)

The pollen grains are monads, medium-sized, heteropolar, and monoporate. Polar diameter is 25.64 ± 2.07 µm, equatorial diameter is 36.25 ± 2.33 µm, with a P/E ratio of 0.707 (oblate). In polar view, the outline is elliptic. The longest equatorial diameter measures 36.25 ± 2.33 µm. When dry, the pollen takes on a characteristic boat-shaped form with a single sunken pore. The exine surface is psilate to finely granulate or microreticulate (Fig. 4.1h).

3.10. *Rumex pamiricus* (Polygonaceae)

The pollen grains are monads, small, isopolar, and spheroidal. Polar diameter is 20.76 ± 1.28 µm, equatorial diameter is 24.33 ± 1.51 µm, with a P/E ratio of 0.853 (oblate-spheroidal). In polar view, the outline is circular to subcircular. The longest equatorial diameter measures 24.33 ± 1.51 µm. Dry pollen grains are often irregularly infolded. The exine is typically reticulate to micro-reticulate (Fig. 4.1i).

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3.11. *Plantago lanceolata* (Plantaginaceae)

The pollen grains are monads, small, isopolar, spheroidal, and pantoporate. Polar diameter is 15.56 ± 1.19 µm, equatorial diameter is 16.20 ± 1.07 µm, with a P/E ratio of 0.960 (oblate-spheroidal). In polar view, the outline is circular. The longest equatorial diameter measures 16.20 ± 1.07 µm. When dry, the grains appear irregularly infolded. The exine is tectate with psilate to scabrate ornamentation (Fig. 4. 1j).

4. DISCUSSION

The present study demonstrates major interspecific variations in pollen size, shape, and exine ornamentation among 10 plant species from Termez, Uzbekistan. This distinct morphological heterogeneity aligns closely with the established diagnostic features of their respective families, underscoring the reliability of palynological traits for systematic and taxonomic applications. Pollen grains exhibit a broad evolutionary and functional spectrum; as the male gametophytes of spermatophytes, they facilitate sexual reproduction through gamete delivery while simultaneously acting as biological aeroplankton that enable long-distance dispersal. This phenotypic architecture is strictly regulated by an interplay between genetic blueprints and localized environmental selection pressures, directly dictating pollen viability, atmospheric transport dynamics, and systemic utility (Javed et al., 2024; Niazi et al., 2025). Key diagnostic features—including grain dimensions, shape symmetry, apertural configurations, and exine stratification—remain relatively stable, serving as conservative, foundational markers for modern plant systematics and taxon delimitation (Erdtman, 1952). In this context, scanning electron microscopy (SEM) substantially enhances resolution by revealing nanometer-scale exine ultrastructures and intricate tectum ornamentations that are frequently obscured or misinterpreted under conventional light microscopy (Guimarães et al., 2018; Atazadeh & Ghahremaninejad, 2025). Angiosperm pollen exhibits remarkable morphological diversity, with grain sizes spanning from less than 5 µm to well over 200 µm, carrying profound implications for atmospheric transport kinetics, sedimentation rates and geographical gene flow (Park & Song, 2010; Lu et al., 2022).

In our dataset, *Oenothera speciosa* (Onagraceae) exhibited exceptionally large pollen grains characterized by prominent viscin threads, a family-specific adaptation that facilitates pollinator attachment and pollen clumping. Conversely, *Quercus robur* (Fagaceae) displayed a distinctly oblate morphology typical of wind-pollinated taxa, an architectural trait optimized for aerodynamic buoyancy and prolonged atmospheric suspension. Principal Component Analysis (PCA) demonstrated robust discriminatory power, with the first two principal components explaining 99.98% of the total morphometric variance. This clear mathematical segregation based on size and shape vectors validates the application of multivariate morphometrics for definitive taxonomic identification. Our findings closely mirror recent global advancements (2020–2025) exploring palynological variation across diverse geographical gradients. For instance, Qu et al. (2025) investigated 19 species within the subtribe *Inuleae* (Asteraceae) using light microscopy and SEM, demonstrating that pollen size and echinate-microperforate exine variations contribute significantly to interspecific differentiation via PCA and hierarchical clustering. This parallels the high variance explained within our Termez dataset. Similarly, Şeker (2025) analyzed 13 *Gentiana* taxa in Türkiye, utilizing multivariate statistical approaches to confirm pollen shape and exine stratification as highly diagnostic taxonomic markers. Numerous researchers explored pollen morphology across diverse cultivars, successfully linking exine variations to evolutionary origins and genetic relationships, which directly corroborates our observations regarding family-consistent architectural stability. Additional comparative studies further reinforce these patterns. For example, Khan et al. (2022) examined pollen morphometrics of 15 arid-zone species in Pakistan, highlighting similar size and sculpturing adaptations to high-temperature and low-humidity conditions as observed in the city of Termez samples. In East Asia, Wang et al. (2023) documented pollen diversity in 22 desert steppe taxa from Inner Mongolia, where PCA also accounted for over 98% variance, emphasizing the conserved role of exine ornamentation under extreme aridity. These international works collectively validate that pollen traits remain reliable taxonomic indicators even across contrasting climatic zones. Biologically, pollen morphology directly impacts reproductive success and fitness. Large grains, such as those of *Oenothera*, possess substantial nutrient reserves to support rapid pollen tube kinetics but disperse less readily through the air, relying instead on specialized zoophilous vectors. Conversely, smaller, oblate grains—exemplified by *Quercus*—minimize aerodynamic drag, thereby enhancing atmospheric buoyancy and anemophilous dispersal efficiency. Exine ornamentation patterns (echinate, reticulate, rugulate) dictate mechanical adhesion to vectors, facilitate stigma recognition, and provide critical protection against desiccation and solar UV radiation. Ecologically, these variations play a pivotal role in shaping dispersal kernels, gene flow, and community assembly, particularly within hyper-arid corridors like the Surkhandarya Region. In desert environments, a robust, highly structured exine is essential for maintaining cellular viability during long-distance atmospheric transport under intense thermal and dust loads. Pollen morphological diversity promotes ecological resilience by enabling species to exploit different pollination syndromes and dispersal strategies, thereby reducing competition and enhancing coexistence in resource-limited habitats. Furthermore, as

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sensitive bioindicators, pollen traits reflect environmental changes: climate-induced stresses can delay flowering phenology and alter exine development along altitudinal and latitudinal gradients. Airborne pollen, as a major component of biological aeroplankton, also influences regional air quality, allergenicity, and even cloud microphysics through ice-nucleation processes.

Despite its novel contributions to the palynology of Central Asia, this study possesses certain limitations. We examined only 10 species over a single vegetative season, which restricts the immediate generalizability of the dataset. Pollen traits can exhibit minor intraspecific or environment-driven plasticity; for example, localized soil attributes and edaphic conditions have been shown to modify exine micro-traits. Consequently, single-season sampling may overlook interannual variations driven by macroclimatic fluctuations, while the relatively small sample size risks missing rare morphotypes or subtle shifts induced by extreme weather events. To address these limitations, future multi-year, multi-site palynological initiatives must be extended across Uzbekistan's unique flora, incorporating molecular markers and broader environmental data. Such comprehensive baselines are essential to strengthen practical applications in regional aeropalynological monitoring. Precise species-level identification of airborne pollen is critical for constructing localized pollen calendars, assessing allergen loads, and monitoring air quality in arid urban settings such as Termez, where frequent dust storms intermix with biogenic particles. By mapping precise ultrastructural features via SEM, public health frameworks can better predict the seasonal onset of pollinosis and respiratory allergies, enabling targeted preventative measures. Moreover, integrating these morphometric vectors into automated aerosol sampling networks and AI-driven identification systems can significantly enhance the accuracy of real-time bio-monitoring. This transformation turns basic palynological data into a powerful tool for urban environmental management, public health policy, epidemiological forecasting, and biodiversity conservation strategies across the Surkhandarya Region and broader Central Asia.

5. CONCLUSION

This study provides the first systematic, high-resolution SEM-based characterization of pollen morphology and exine ultrastructure for 10 ecologically dominant plant species from Termez, southern Uzbekistan. Quantitative morphometric analysis revealed significant interspecific variations in polar diameter (14.89 µm to 112.67 µm) and geometric shape vectors, which were mathematically validated by Principal Component Analysis to explain 99.98% of the total morphometric variance. Coupled with qualitative exine sculpture variations (e.g., reticulate, rugulate, and viscin thread configurations), these findings demonstrate exceptional taxonomic resolution, confirming that ultrastructural palynological traits provide definitive criteria for species-level delimitation within arid-zone floras. The principal novelty of this investigation lies in establishing the first ultrastructural palynological baseline for this ecologically vital and hyper-arid corridor of Central Asia, directly bridging a long-standing geographical knowledge gap previously constrained by low-resolution light microscopy. By delivering an empirical, high-fidelity digital morphometric dataset, this research establishes the foundational infrastructure required to initiate the national Pollen Atlas of Uzbekistan. The practical and future applications of this baseline dataset extend across several environmental and public health sectors:

Aeropalynological Monitoring & Allergology: These metrics enable the optimization of localized automated pollen monitoring networks and the construction of precise seasonal pollen calendars, directly enhancing type I hypersensitivity allergy forecasting and preventative clinical interventions in urban drylands.

Urban Landscaping & Environmental Management: The diagnostic matrix informs sustainable urban planning by guiding the selection of low-allergenic, drought-resilient vegetation for smart greening initiatives, while establishing pollen as a high-resolution bioindicator for atmospheric dust-pollen interactions and environmental stress.

Conservation & Systematic Frameworks: The dataset advances forensic palynology and melissopalynology applications within Central Asia, supporting regional biodiversity conservation programs.To build upon these insights, future research directions must expand the palynological repository to encompass a broader spectrum of local and cross-border taxa. Furthermore, implementing multi-site, longitudinal aeropalynological tracking is essential to systematically assess the long-term impacts of climate change, altitudinal shifts, and rapid urbanization on regional pollen phenology, airborne composition, and allergenicity dynamics across Central Asia.

Declarations

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