sustainability

MDPI

Editorial

Palynology for Sustainability: A Classical and Versatile Tool for New Challenges: Editorial

Assunta Florenzano [1], Eleonora Clò [1,*], Gabriel Servera-Vives [2] and Anna Maria Mercuri [1]

[1] Laboratorio di Palinologia e Paleobotanica, Dipartimento Scienze della Vita, Università degli Studi di Modena e Reggio Emilia, 41125 Modena, Italy; assunta.florenzano@unimore.it (A.F.); annamaria.mercuri@unimore.it (A.M.M.)
[2] ArqueoUIB, Department of Historical Sciences and Theory of Art, University of the Balearic Islands, 07122 Palma, Spain; gabriel.servera@uib.cat
* Correspondence: eleonora.clo@unimore.it

Abstract: This Special Issue presents interdisciplinary studies in applied palynology, highlighting the use of pollen as a tool for understanding environmental conditions across various contexts. Contributions include applications of pollen as a bioindicator for chemical pollution, human impact, and other variables. Several articles focus on the use of pollen in archaeological research, environmental health, and air quality monitoring, such as in Rome and Bologna, analysing long-term trends in allergenic pollen concentrations and airborne allergens. Additionally, studies of modern analogues in Mediterranean landscapes and in Southern Oman illustrate how modern pollen helps reconstruct vegetation history and land uses, and assess ecological changes. Overall, the contributions underscore the importance of pollen in environmental monitoring, sustainability research, and human health protection.

Keywords: pollen; botany; biodiversity; palaeoecology; Mediterranean; human impact; environmental change; sustainability; air quality monitoring; environmental pollution

1. Introduction

This Special Issue presents articles covering different topics on the subject of pollen across different fields of "applied palynology". Mercuri [1] reports a gap "between research on pollen as an object (basic palynology) and research with pollen as a measurement tool (applied palynology)". Accordingly, palynology plays an incontrovertible role not only in "basic research" concerning botanical taxonomy, phylogeny, phenology and reproductive biology, but also in several fields of applied research that focus on measuring environmental variables. Jimenez-Zamora et al. [2] integrated this approach into interdisciplinary palynology, suggesting that a wide range of possible applications makes this science a crucial approach for understanding synergies between ecosystem services and landscape management. The literature contains many examples of agrarian landscape reconstructions and historical ecology studies focusing on sustainability. Several palynological applications deal with agrobiodiversity conservation, pollinators and melissopalynology, and the preservation of native species, often outlining the connection between food, non-food, and natural resources to develop a sustainable economy at the local level. Less extended fields of applied palynology are avian palynology, pollen from burials and ritual contexts, garden palynology, and contexts of specific interest for forensic sciences.

Applied palynology focuses on using pollen as a measure of, for example, floristic richness, the quality of food and air especially in relation to allergies, and the presence

check for updates

Received: 15 February 2025
Accepted: 20 February 2025
Published: 25 February 2025

Citation: Florenzano, A.; Clò, E.; Servera-Vives, G.; Mercuri, A.M. Palynology for Sustainability: A Classical and Versatile Tool for New Challenges: Editorial. *Sustainability* **2025**, *17*, 1938. https://doi.org/10.3390/su17051938

of air or soil pollution, e.g., [3–6]. Interesting applications in the study of archaeological contexts have revealed the potential to uncover sustainability strategies used in the past [7]. On one hand, pollen and other microremains are known to be evident 'proxy indicators' of environmental conditions, both in past and modern contexts, see, for example, [8,9]. On the other hand, aerobiology, alongside palaeoecology, is a prominent field, demonstrating the significant potential of pollen as a methodological approach to add detail and information to other methods.

This Special Issue explores some uncommon aspects of applied palynology, demonstrating that palynology allows us to explore seemingly distant areas and environments pervaded by plants, the primary sources of pollen production.

2. Synopsis of Contributions

This Special Issue brings together eight contributions, presenting a selection of quite different interdisciplinary studies where pollen is used in combination with other proxies in applied palynology.

Florenzano et al. (Contribution 1) focus on millets, small-sized cereals generally considered of minor importance in the human diet. Nevertheless, they are thought to have played an important role in the late Bronze Age due to their greater drought tolerance compared to other cereals, subsequently spreading across Europe [10,11]. Besides the study of seeds, molecular residues are largely used in current archaeological research to detect the presence or translocation of domesticated *Panicum miliaceum* [12]. In this article, the authors present an unprecedented combination of palynological and molecular studies, combining rare discoveries of *Panicum* pollen with organic residues of miliacin in the same stratigraphic levels near a Bronze Age site in Emilia-Romagna, northern Italy. This pollen is quite ambiguous, and the identification of the domesticated millet only based on pollen morphology is not conclusive. Moreover, the chemical residues are not diagnostic, as several wild plants can also produce miliacin. The authors propose an interesting approach by investigating the simultaneous presence of the two proxies, suggesting that only this double evidence can be taken as reliable evidence of millet cultivation in past contexts.

Braga et al. (Contribution 2) outline the use of pollen as a bioindicator of chemical pollution in the "Laghi di Mantova e Polo Chimico" area in the city of Mantua, Lombardy, northern Italy. Despite its classification as an area 'of national interest', the site has been highly polluted by industries that use the lakes' water. This article demonstrates that the effects of anthropogenic impact on local vegetation are evident at both macroscopic and microscopic levels. The study integrates the floristic survey of selected sectors around the lakes with the palynological study of the plants growing in the same sectors. The flora of highly contaminated sectors was surveyed, and the floristic composition and ecological (CSR) strategies of the species were compared with a control sector. The protected species *Narcissus pseudonarcissus* L. was found in the control sector. Pollen preservation of the selected species was assessed as a bioindicator of environmental health in the same sectors. The data confirmed once again that the state of preservation of pollen is a reliable indicator of environmental stress. For example, the incidence of pollen without cytoplasm is higher in polluted areas. This article contributes further to the growing field of ecological palynology [13], presenting a newly structured application of pollen analysis based on the evidence that environmental pollution leads to increased abortion rates and mutagens in plant reproductive cycles.

Servera-Vives et al. (Contribution 3) addresses a classic theme of pollen as a bioindicator of anthropogenic activities [14–17] and outlines it expertly in a very complex context: the Mediterranean islands. The article introduces anthropogenic pollen indicators for the Balearic Islands, also assessing possible gradients of human impact on vegetation in the

Mediterranean islands. The highly detailed study follows research by the same authors on modern analogues to understand pollen–vegetation dynamics in a Mediterranean mosaic landscape [18]. In this article, studies on modern pollen analogues are complemented by statistical techniques, phytosociological descriptions, and both quantitative and presence/absence data. Alongside understanding land use dynamics, this research proposes region-specific API indicators linked to several human impact degrees. In the case study of the Balearic Islands, this approach helps assess the rhythms of anthropization in the Mediterranean islands.

Di Menno di Bucchianico et al. (Contribution 4) contribute to the understanding of airborne pollen concentration over a long-term series of air monitoring stations. The monitoring stations of the Aerobiological Monitoring Center of Tor Vergata are in the unique urban context of Rome. Data on the trends of the main allergenic pollen and *Alternaria* spores were collected from 2003 to 2019, a significantly long period that allows for the observation of changes in pollen rain seasons. The highest average concentration was found for Cupressaceae/Taxaceae, followed by Urticaceae and Poaceae. Statistical analysis showed consistent trends across two monitoring stations, indicating a general territorial trend rather than local phenomena. Notable decreasing trends were observed for Asteraceae, Cupressaceae/Taxaceae, and *Alternaria*, while Betulaceae showed an increasing trend at one station. The results emphasise the importance of including biological particulates in air quality assessments to better understand their effects on human health [19].

Miraglia et al. (Contribution 5) report on a different aspect of the same monitoring stations, highlighting the complexity of Rome's urban flora, which is reflected in the composition of the pollen seasons and the corresponding pollinosis [20]. Interestingly, as the city has a very large area, the three monitoring stations show interesting differences in pollen composition, depending on the local flora. The pollen data of selected taxa from 2020 and 2021 were compared, and the diversity observed among the three stations indicates a phenological succession in accordance with the microclimatic variations across the different districts of the city. Airborne pollen concentration heterogeneity reflects floristic diversity, with qualitative and quantitative parameters showing a consistent flowering trend aligned with species seasonality. The study emphasises the need for more sampling points in Italy to improve data localization [21] and enhance health protection, as well as support the management and conservation of green spaces.

Clò and Florenzano (Contribution 6) point to the key importance of non-pollen palynomorphs, in addition to pollen, for understanding local ecological conditions in stratigraphy [22,23]. The combination of algal remains with pollen from wetland plants is especially useful for reconstructing local variability and rapid ecological conditions over millennia of deposition. The study focuses on the cyanobacterium *Rivularia*, belonging to an easily recognisable type and including different morphologies. *Rivularia* can fossilise due to its thick envelope, which ensures the preservation of heterocysts in sediments. Samples were taken from cores spanning the last 15 ka years, close to the Terramara S. Rosa di Poviglio, in northern Italy [24,25]. The results highlight that this non-pollen palynomorph, associated with increased eutrophication and water changes in soil, serves as an effective bioindicator of local agricultural activities and the presence of livestock.

Suanno et al. (Contribution 7) evaluated airborne pollen, allergens, and protein levels in Bologna, Italy, during the grass flowering period, using three sampling devices: a Cyclone sampler (CS), a Dicothomous sampler (DS), and a Berner impactor (BI). The study aimed to assess the association between pollen concentrations, allergen levels, and meteorological and chemical parameters. Proteins were extracted from aerosol samples, and grass allergens Phl p 1 and Phl p 5 were quantified by ELISA. Results showed that protein and allergen concentrations were approximately ten times higher in samples collected by CS compared

to DS and BI, likely due to differences in cut-offs. While airborne proteins did not correlate with Poaceae pollen or its allergens, aeroallergens correlated with pollen only in the coarse particulate fraction, suggesting the presence of pollen-independent aeroallergens in the fine particulate, influenced by high wind speeds.

Bellini et al. (Contribution 8) examine the flora and vegetation of estuaries along the Dhofari coast in Southern Oman, with a particular focus on plants growing on different substrates. Archaeobotanical studies reveal that mangroves, including *Rhizophora* and *Avicennia*, were more widespread along Oman's southeastern coast 6000 years ago. *A. marina* communities, like archaeological sites, are a crucial cultural heritage that must be preserved [26]. Many estuaries still host mangroves (*Avicennia marina* Forssk.), a fragile ecosystem threatened by current environmental changes, while other areas support a rich flora influenced by the monsoon. The authors analysed surface soil samples to investigate pollen diffusion and its representation in modern pollen rain, relating pollen abundance to the coverage of plant species typical of each environment. The pollen records provide a general overview of the area's vegetation, offering valuable insights for interpreting past pollen records and supporting the use of pollen analysis in reconstructing vegetation history. The Supplementary Materials of this article include an important atlas of pollen morphology featuring over 40 species, along with high-quality photographs that can aid in pollen identification for applied research in Oman.

3. Conclusions

In conclusion, this Special Issue highlights the growing significance of applied palynology across various fields, demonstrating its potential as a versatile tool for understanding environmental dynamics, human impact, and ecological changes. The integration of pollen analysis with other proxies has proven valuable in a range of interdisciplinary studies, from monitoring air quality and assessing allergenic risks to reconstructing past landscapes and investigating pollution levels. These findings emphasise the importance of incorporating pollen as a bioindicator in both modern and historical contexts [27], offering insights into sustainability, biodiversity conservation, and environmental health. The continued advancement of palynological techniques, coupled with the expansion of their applications, will further enhance our understanding of ecological systems and support more informed strategies for managing and protecting natural resources.

Author Contributions: The authors contributed equally to this Editorial and co-edited the Special Issue on "Palynology for Sustainability: A Classical and Versatile Tool for New Challenges" (https://www.mdpi.com/journal/sustainability/special_issues/palynology_for_sustainability, accessed on 20 February 2025). All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The SI reports some papers awarded during the conference MedPalynoS-2021, and others presented in the following editions. We are very grateful to the different authors for their valuable contribution to this Special Issue. We warmly thank all the reviewers who dedicated time and assisted in improving the manuscripts. This Special Issue was partially funded by the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 895735. This research was funded by the project "National Biodiversity Future Center—NBFC", implemented under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4—Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union—Next Generation EU. Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022, adopted by the Italian Ministry of University and Research, CUP E93C22001090001.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Florenzano, A.; Clò, E.; Jacob, J. Pollen and Molecular Biomarkers from Sedimentary Archives in the Central Po Plain (N Italy): Assessing Their Potential to Deepen Changes in Natural and Agricultural Systems. *Sustainability* **2023**, *15*, 10408.
2. Braga, L.; Furia, E.; Buldrini, F.; Mercuri, A.M. Pollen and Flora as Bioindicators in Assessing the Status of Polluted Sites: The Case Study of the Mantua Lakes (SIN "Laghi di Mantova e Polo Chimico"; N Italy). *Sustainability* **2023**, *15*, 9414.
3. Servera-Vives, G.; Mus Amezquita, M.; Snitker, G.; Florenzano, A.; Torri, P.; Ruiz, M.; Mercuri, A.M. Human-Impact Gradients through Anthropogenic Pollen Indicators in a Mediterranean Mosaic Landscape (Balearic Islands). *Sustainability* **2023**, *15*, 8807.
4. Di Menno di Bucchianico, A.; Gaddi, R.; Brighetti, M.A.; De Franco, D.; Miraglia, A.; Travaglini, A. Status and Trend of the Main Allergenic Pollen Grains and *Alternaria* Spores in the City of Rome (2003–2019). *Sustainability* **2023**, *15*, 6150.
5. Miraglia, A.; Brighetti, M.A.; Franco, D.D.; Di Menno di Bucchianico, A.; Froio, F.; Travaglini, A. Multiple Monitoring Stations in Big Cities: First Example of Three Spore Traps in Rome. *Sustainability* **2023**, *15*, 4155.
6. Clò, E.; Florenzano, A. Heterocysts of *Rivularia* Type for Interpreting a Palaeoenvironmental Context of the Late Quaternary in Northern Italy. *Sustainability* **2022**, *14*, 15332.
7. Suanno, C.; Sandrini, S.; Aloisi, I.; De Nuntiis, P.; Facchini, M.C.; Del Duca, S.; Fernández-González, D. Airborne Pollen, Allergens, and Proteins: A Comparative Study of Three Sampling Methods. *Sustainability* **2022**, *14*, 11825.
8. Bellini, C.; Ciani, F.; Pignotti, L.; Baldini, R.M.; Gonnelli, T.; Mariotti Lippi, M. Modern Pollen Analysis in the Estuary Habitats along the Coast of Dhofar (Sultanate of Oman). *Sustainability* **2022**, *14*, 11038.

References

1. Mercuri, A.M. Applied palynology as a trans-disciplinary science: The contribution of aerobiology data to forensic and palaeoenvironmental issues. *Aerobiologia* **2015**, *31*, 323–339. [CrossRef]
2. Jiménez-Zamora, T.; Galicia, L.; Espinosa, D.; Rivera-González, I.; Luna-Vega, I. Understanding perspectives of current palynology: Using science with practical discourse. *Bot. Sci.* **2023**, *101*, 341–357. [CrossRef]
3. Fægri, K.; Iversen, J.; Kaland, P.E.; Krzywinski, K. *Textbook of Pollen Analysis*, 4th ed.; The Blackburn Press: Caldwell, ID, USA, 1989.
4. Clò, E.; Furia, E.; Florenzano, A.; Mercuri, A.M. Flora-vegetation history and land use in Medieval Tuscany: The palynological evidence of a local biodiversity heritage. *Quat. Int.* **2024**, *705*, 1–15. [CrossRef]
5. Rojo, J.; Cervigón, P.; Ferencova, Z.; Cascón, Á.; Galán Díaz, J.; Romero-Morte, J.; Sabariego, S.; Torres, M.; Gutiérrez-Bustillo, A.M. Assessment of environmental risk areas based on airborne pollen patterns as a response to land use and land cover distribution. *Environ. Pollut.* **2024**, *344*, 123385. [CrossRef]
6. Kato, Y.; Morikawa, T.; Fujieda, S. Comprehensive review of pollen-food allergy syndrome: Pathogenesis, epidemiology, and treatment approaches. *Allergol. Int.* **2025**, *74*, 42–50. [CrossRef] [PubMed]
7. Mercuri, A.M.; Florenzano, A.; Clò, E. Sustainability in the Neolithic and the Bronze Age Through the Lens of Archaeobotany. In *The Palgrave Handbook of Global Sustainability*; Brinkmann, R., Ed.; Palgrave Macmillan: Cham, Switzerland, 2023; pp. 2249–2262. [CrossRef]
8. Innes, J.B. Climate Change and Vegetation Evolution During the Holocene: Editorial. *Quaternary* **2025**, *8*, 1. [CrossRef]
9. Mercuri, A.M.; Florenzano, A.; Clò, E.; Servera-Vives, G. Palynology for Sustainability: A Classical and Versatile Tool for New Challenges—Recent Progress. *Quaternary*, 2025, *submitted*.
10. Filipović, D.; Meadows, J.; Dal Corso, M.; Kirleis, W.; Alsleben, A.; Akeret, Ö.; Bittmann, F.; Bosi, G.; Ciută, B.; Dreslerová, D.; et al. New AMS 14C dates track the arrival and spread of broomcorn millet cultivation and agricultural change in prehistoric Europe. *Sci. Rep.* **2020**, *10*, 13698. [CrossRef] [PubMed]
11. Dal Corso, M.; Zanon, M.; Heron, C.; Rottoli, M.; Cupitò, M.; Dalla Longa, E.; Kirleis, W. Tracing millet through biomarker analysis in archaeological sites in alluvial plains: The first miliacin data from the northern Italian Bronze Age. In *Millet and What Else? The Wider Context of the Adoption of Millet Cultivation in Europe*; Kirleis, W., Dal Corso, M., Filipović, D., Eds.; Sidestone Press: Leiden, The Netherlands, 2022; pp. 231–252.
12. Standall, E.A.; Craig, O.E.; Kneisel, J.; Müller, J.; Kirleis, W.; Czebreszuk, J.; Heron, C. Millet and meals: The role and significance of Panicum miliaceum in culinary contexts at Bruszczewo, Poland. *Archaeol. Anthropol. Sci.* **2025**, *17*, 274512096. [CrossRef] [PubMed]

13. Vasilevskaya, N. Pollution of the Environment and Pollen: A Review. *Stresses* **2022**, *2*, 515–530. [CrossRef]
14. Behre, K.-E. The Interpretation of Anthropogenic Indicators in Pollen Diagrams. *Pollen Spores* **1981**, *23*, 225–245.
15. Mercuri, A.M.; Bandini Mazzanti, M.; Florenzano, A.; Montecchi, M.C.; Rattighieri, E.; Torri, P. Anthropogenic Pollen Indicators (API) from archaeological sites as local evidence of human-induced environments in the Italian peninsula. *Ann. Bot.* **2013**, *3*, 143–153. [CrossRef]
16. Deza-Araujo, M.; Morales-Molino, C.; Tinner, W.; Henne, P.D.; Heitz, C.; Pezzatti, G.B.; Hafner, A.; Conedera, M. A Critical Assessment of Human-Impact Indices Based on Anthropogenic Pollen Indicators. *Quat. Sci. Rev.* **2020**, *236*, 106291. [CrossRef]
17. Deza-Araujo, M.; Morales-Molino, C.; Conedera, M.; Henne, P.D.; Krebs, P.; Hinz, M.; Heitz, C.; Hafner, A.; Tinner, W. A New Indicator Approach to Reconstruct Agricultural Land Use in Europe from Sedimentary Pollen Assemblages. *Palaeogeogr. Palaeoclim. Palaeoecol.* **2022**, *599*, 111051. [CrossRef]
18. Servera-Vives, G.; Mus Amezquita, M.; Snitker, G.; Florenzano, A.; Torri, P.; Estrany Bertos, J.; Mercuri, A.M. Modern Analogs for Understanding Pollen-Vegetation Dynamics in a Mediterranean Mosaic Landscape (Balearic Islands, Western Mediterranean). *Holocene* **2022**, *32*, 716–734. [CrossRef]
19. Glick, S.; Gehrig, R.; Eeftens, M. Multi-decade changes in pollen season onset, duration, and intensity: A concern for public health? *Sci. Total Environ.* **2021**, *781*, 146382. [CrossRef] [PubMed]
20. Brighetti, M.A.; De Franco, D.; Di Cosmo, C.; Di Menno di Bucchianico, A.; Froio, F.; Miraglia, A.; Moselli, D.; Travaglini, A. Aerobiological Biodiversity in the Metropolitan City of Rome. *Int. J. Environ. Sci. Nat. Res.* **2022**, *30*, 556283. [CrossRef]
21. Vélez-Pereira, A.M.; De Linares, C.; Belmonte, J. Aerobiological modelling II: A review of long-range transport models. *Sci. Total Environ.* **2022**, *845*, 157351. [CrossRef]
22. van Geel, B. Application of fungal and algal remains and other microfossils in palynological analyses. In *Handbook of Holocene Palaeoecology and Palaeohydrology*; Berglund, B.E., Ed.; John Wiley & Sons, Inc.: Chichester, UK, 1986; pp. 497–505.
23. van Geel, B. The paleo-environmental indicator value of non-pollen palynomorphs in lake sediments, peat deposits, and archaeological sites. *Pollen* **2004**, *14*, 276–277.
24. Cremaschi, M.; Mercuri, A.M.; Benatti, A.; Bosi, G.; Brandolini, F.; Clò, E.; Florenzano, A.; Furia, E.; Mariani, G.S.; Mazzanti, M.; et al. The SUCCESSO-TERRA Project: A lesson of sustainability from the Terramare culture, the Middle Bronze Age of the Po Plain (Northern Italy). *IANSA* **2018**, *9*, 59–67. [CrossRef]
25. Clò, E. Climate Change and Human Impact in a Long-Term Perspective: Palynology of Central Po Plain Deposits Since the Lateglacial. Ph.D. Thesis, Università degli Studi di Modena e Reggio Emilia, Modena, Italy, 2022.
26. Lézine, A.M.; Saliège, J.-F.; Mathieu, R.; Tagliatela, T.L.; Méry, S.; Charpentier, V.; Cleuziou, S. Mangroves of Oman during the late Holocene: Climatic implications and impact on human settlements. *Veg. Hist. Archaeobot.* **2002**, *11*, 221–232. [CrossRef]
27. Izdebski, A. Chapter 2 Palynology and Historical Research. In *A Companion to the Environmental History of Byzantium*; Izdebski, A., Preiser-Kapeller, J., Eds.; Brill: Leiden, The Netherlands, 2024; pp. 59–82. [CrossRef]