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Utilization of Herbaria in Ecological Studies: Biodiversity and Landscape Monitoring

Herbaryumun Ekolojik Çalışmalarda Kullanımı: Biyoçeşitlilik ve Alan İzleme

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ABSTRACT

Herbaria collections—systematic repositories where plant specimens are preserved—are transitioning from traditional taxonomic tools into fundamental resources in ecological research. This comprehensive review summarizes multidisciplinary applications of herbaria collections in monitoring biodiversity and conservation. The review evaluates the historical and contemporary importance of herbaria specimens in documenting changes in species distribution, population dynamics, and community composition, elucidating their roles in understanding the effects of climate change and human intervention. Moreover, it examines how herbaria collections contribute to large-scale temporal and spatial biodiversity analyses, predictive modeling, and conservation planning in the context of advancements in digitization and molecular techniques. This review underscores the integration of herbaria data into mainstream ecological research and policy decisions, advocating for modernizing herbarium techniques and the innovative use of collections. It aims to foster a deeper understanding of complex environmental systems and inform targeted conservation strategies by revealing the multifaceted uses and expectations of herbaria in ecological studies. Thus, it contributes to the broader scientific discussion on sustainable biodiversity management and highlights the relationship between herbaria and ecological studies.

Keywords: Biodiversity, Conservation Planning, Ecology, Herbarium, Monitoring

ÖZ

Herbaryumların koleksiyonları, bitki örneklerinin korunduğu sistematik depolar, geleneksel taksonomik araçlardan ekolojik araştırma alanında temel kaynaklara dönüşmektedir. Bu kapsamlı inceleme, herbaryumların biyoçeşitlilik izleme ve koruma konularında çok disiplinli uygulamalarını bir araya getirmektedir. Türlerin dağılımı, popülasyon dinamikleri ve topluluk bileşimindeki değişiklikleri belgeleme konusunda herbaryum örneklerinin tarihsel ve güncel önemini kritik bir şekilde değerlendirmektedir, özellikle iklim değişikliği ve insan müdahalesinin etkilerini anlamada rollerini açıklamaktadır. Dijitalleştirme ve moleküler tekniklerdeki son gelişmeler sonucunda, herbaryumların koleksiyonları büyük ölçekli zamansal ve mekansal biyoçeşitlilik analizlerine, öngörü modellerine ve koruma planlamasına nasıl katkı sağladığı incelenmektedir. Bu inceleme, herbaryumlara ait verilerin ana akım ekolojik araştırma ve politika kararlarına zorunlu entegrasyonunu vurgular, herbaryum tekniklerinin modernleştirilmesi ve mevcut koleksiyonların yenilikçi kullanımını belirtmektedir. Kompleks çevresel sistemlerin daha derin bir anlayışını teşvik etmeyi amaçlar ve herbaryumların ekolojik çalışmalardaki çok yönlü kullanım ve beklentilerini ortaya koyarak hedeflenen koruma stratejilerine katkı sağlar. Böylece, sürdürülebilir biyoçeşitlilik yönetimi üzerine geniş bilimsel tartışmaya katkı sağlayıp herbaryumlar ile ekolojik çalışmalar arasındaki ilişkiyi vurgular.

Anahtar Kelimeler: Biyoçeşitlilik, Ekoloji, Herbaryum, İzleme, Koruma Planlaması

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INTRODUCTION

The diversity and distribution of plant species have profound implications for the ecosystem, ranging from nutrient cycling to wildlife habitat (Sanderson et al., 2004). Understanding these dynamics is crucial for effective conservation, ecological modeling, and environmental policy development. However, capturing a complete picture of plant diversity, distribution, and change over time can be an immense challenge. This is where the unique potential of herbaria collections comes into focus. For centuries, herbaria collections have been important in botanical science as repositories for plant specimens and taxonomic research (Brock et al., 2009). Traditionally, herbaria were used to describe and classify plant species, providing a critical reference for botanists and researchers (Belhumeur et al., 2008).

In recent decades, herbaria collection shave transcended their classical role, becoming a dynamic tool in ecological studies. Herbaria collections now serve as historical records of biodiversity, offering information about species distribution, population dynamics, and ecological preferences, as well as response to climate change, which poses a severe threat to our water resources (Çelekli & Zariç, 2023; Gallagher et al., 2009; Jones & Daehler, 2018). The convergence of traditional herbarium techniques with modern technologies, such as digitization, molecular analysis, and geographical information systems (GIS), has created unprecedented research opportunities, particularly in biodiversity monitoring and conservation. Despite these opportunities, some challenges and limitations must be recognized. Issues related to preservation quality, accessibility, and funding have become concerns in the herbarium community. Furthermore, there is a growing need for collaboration among institutions and integration of herbarium data into broader ecological research and decision making.

This review examines the multifaceted roles of herbaria collections in contemporary ecological studies; evaluates how herbaria have been utilized for biodiversity and landscape monitoring, conservation planning, and broader ecological inquiries; and evaluates the challenges faced by herbaria collections, advocating for strategic efforts to maximize their potential.

Herbaria Specimens: Bridging Historical Taxonomy and Modern Ecological Insights

Herbaria play a crucial role in scientific research because they contain dried, classified, and preserved plant specimens (Friedman et al., 1986). They hold immense scientific value, finding applications in traditional taxonomy and contemporary ecological studies (Lavoie, 2013). The historical significance of herbaria lies in their contribution to early taxonomy and classification, which laid the foundation for modern plant science. These collections offer glimpses into historical biodiversity and changes in plant distributions, serving as references for assessing long-term ecological shifts. Notably, herbaria aided the botanical discoveries of explorers and naturalists, serving as a cornerstone of their findings (Henderson 2011; Greve et al. 2016). Today, herbaria have evolved beyond taxonomy into ecological research. They contribute to conservation genetics by housing genetic material, enabling studies on past genetic diversity, and supporting conservation efforts (DeSalle & Amato, 2004). Moreover, they offer historical baseline data for tracking changes in plant distributions and habitats, thus assisting in contemporary conservation planning (Lang et al., 2019). The effects of climate change, which causes serious problems, such as migration, can be detected on plant diversity through herbaria materials (Schmidt et al. 2005; Çelekli et al. 2023). Climate change studies too benefit from herbarium specimens. These collections provide historical context, helping scientists analyze changes in plant phenology and distribution because of shifting climatic conditions, aiding in predicting future ecological impacts and devising adaptation strategies.

Herbaria facilitate public engagement and education by providing tangible evidence of biodiversity changes and ecosystem shifts. Herbaria raise awareness on preserving and understanding plant diversity through educational outreach. In the context of taxonomy, herbaria specimens continue to serve as fundamental tools for species identification, description, and classification. They aid in discerning species boundaries, conducting taxonomic revisions, and investigating geographical variations (Albani Rocchetti et al., 2021; Heberling, 2022). Transitioning to ecological applications, herbaria are repositories of historical biodiversity data, enabling tracking of ecological changes over time (Lang et al., 2019). Additionally, these collections contribute to studies on shifts in plant distribution in response to climate change, providing insights into the impact of environmental alterations on ecosystems (Lima et al., 2021).

In conclusion, herbaria represent an invaluable resource in scientific exploration. Their historical significance extends from early taxonomy to contemporary ecological investigations. As repositories of botanical heritage, they offer a bridge between the past and present, enriching our understanding of biodiversity, ecosystems, and the ongoing challenges posed by environmental changes.

HERBARIA, BIODIVERSITY, AND LANDSCAPE MONITORING

Landscape monitoring plays a critical role in understanding the health of ecosystems and making informed decisions for conservation (Bogart, 2008).

Methods and Technologies for Tracking Species Distribution and Status

Herbaria specimens, often representing historical records, provide essential data for tracking changes in species distribution and abundance. These specimens serve as baseline reference, enabling comparisons between past and present distributions. Modern technologies, such as GIS and georeferencing, allow mapping specimen collection locations onto geographic maps, revealing changes in the geographic range of species (Rivers et al., 2010).

Land cover comparisons provide information about land use changes over the years, allowing us to see the difference between land use shifts and plant presence in the same area based on the process variation through herbarium samples and conducted studies. This perspective facilitates a deeper understanding of how land management and ecological factors interact over time. The land cover changes between 1990 and 2018 in Uzungöl, Trabzon, Turkey are shown in Figure 1. This was analyzed using the CORINE Land Cover (European Environment Agency, 2021) data from the Copernicus Land Monitoring Service and visualized using ESRI ArcMap 10.7 software. This combination of satellite data, sensor network data, and land cover data allowed for a thorough examination and intuitive understanding of the spatial distribution and transformation of various land cover types over the studied period. The ecological effects of the changing environmental structure can be identified by comparing herbaria samples collected from vegetation and flora studies around it, with land cover comparisons. Table 1 shows the land cover values and changes. These data can be used to identify endangered species by comparing herbarium data due to changing vegetation area due to human activities.

Use of Digitization and Databasing

Herbaria digitization has transformed the landscape of biodiversity monitoring, offering researchers unprecedented access to valuable specimen information. However, to maximize the utility of herbaria in ecological studies, the integration and centralization of herbarium databases must be considered. This involves consolidating digitized collections from various universities into a unified platform (Thiers et al., 2016). Integrating databases from herbaria can enhance data accessibility and streamline research. Converting various database formats into a standardized program enables efficient data analysis and interpretation. Moreover, advocating to establish a systematic framework where all herbaria systematically dispatch duplicates of their specimens,

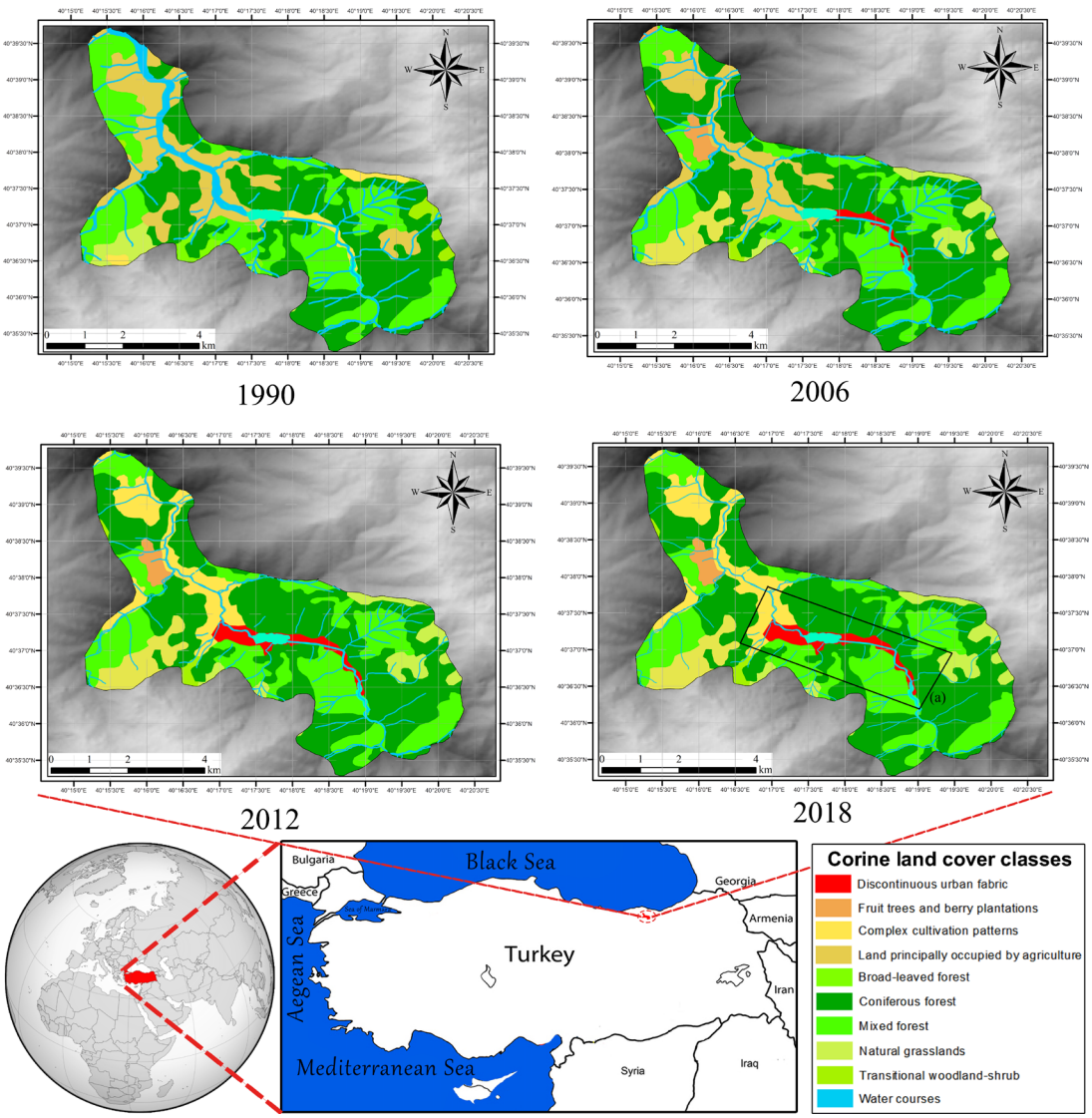

Figure 1. Landcover of Lake Uzungöl from 1990 to 2018, (a) indicates the CORINE quadrate for 1990–2018.

Table 1. Land cover of Lake Uzungöl from 1990 to 2018. Corine data (%) includes urban, agriculture, forestry, and wetland.

	Time (year)			
Landcover	**1990**	**2006**	**2012**	**2018**
Urban	0.75	4.05	8.45	12.94
Agriculture	7.23	5.49	4.01	3.58
Forestry	31.30	30.69	28.96	28.38
Wetland	60.71	59.77	58.58	55.10

particularly those associated with newly identified species and records, to centralized herbarium hubs, is important (Davis, 2023). This procedural norm guarantees the conservation of genetic material for subsequent studies and serves as a robust safeguard against loss. Implementing meticulously designed methods for the storage and maintenance of samples at centralized herbarium locations significantly enhances the viability of ecological research efforts (Soltis, 2017). Databases that allow for large-scale ecological analysis and observation can be created by translating physical specimen information into digital form. The digitization of herbaria samples provides researchers quicker and more efficient access. Digitization facilitates access and serves as a model for other researchers in their digitization efforts (Çiftçi et al., 2023). This streamlines the research process and opens avenues for understanding shifts in species occurrence and habitat preference. With the availability of these data on online platforms, researchers are now equipped with more robust tools to engage in complex studies, underscoring the profound impact of digitization on expanding our ecological knowledge and capabilities.

In summary, advocating to centralize digitized herbaria collections and establishing standardized specimen duplication and storage practices will significantly contribute to advancing ecological studies. This collaborative approach not only enhances data integration and accessibility, but also safeguards the integrity of biodiversity information for future generations of researchers (James et al., 2018).

Analysis of Global Biodiversity and Predictive Modeling

Consolidating digitized herbaria data from diverse sources has paved the way for global biodiversity analyses (James et al., 2018). Researchers can analyze large datasets to identify trends, track invasive species, and assess the impact of land use change. Algae have diverse ecological and biotechnological significance, including their ability to absorb harmful molecules and function as primary producers (Zariç et al., 2022). However, some of them can be invasive (Moss, 1983). Geographic profiling (GP) (with the "Rossmo formula") was effective in assessing the spread of invasive *Caulerpa* in the Mediterranean region (Papini et al., 2013). This suggests that GP is a more practical search strategy in identifying the source populations of invasive species; fueled by datasets, predictive modeling enables scientists to anticipate species responses to climate change and other environmental shifts (Santosuosso & Papini, 2018; Stevenson et al., 2012).

Case Studies

Several case studies have demonstrated the effectiveness of herbaria specimens in biodiversity monitoring. In Europe, herbaria data have been used to analyze shifts in flowering times due to climate change (Rawal et al., 2015). In Australia, herbaria records have helped identify new distribution patterns of invasive species (Wu et al., 2005).

These case studies underscore the contribution of herbaria collections to ecological research and conservation efforts. As technology advances, herbaria will remain crucial in supporting effective conservation strategies and promoting a deeper understanding of the complex dynamics of our ecosystem.

HERBARIA IN CONSERVATION PLANNING

Conservation planning plays a pivotal role in safeguarding biodiversity and ensuring ecosystem health. In this context, herbaria collections and repositories meticulously preserve plant specimens that emerge as invaluable assets for shaping effective conservation strategies (Nualart et al., 2017). An analysis of herbaria samples facilitates understanding of species identified in the International Union for Conservation of Nature (IUCN) conservation categories. This entails considering ecosystem changes, climatic shifts, and temporal factors using sophisticated land cover models.

Drawing on herbarium specimens in floristic studies and comparing them with their historical counterparts enables the determination of the presence, absence, and number of species vulnerable to global warming and climate change. This analytical approach is important for conservation and management, offering insights into addressing existing and future ecological changes. Herbaria specimens contribute significantly to the identification of areas requiring targeted conservation efforts. Conservationists can identify regions with high species richness, endemism, or critical habitats by analyzing historical distribution data, guiding the allocation of resources for optimal habitat protection and restoration, thereby maximizing conservation outcomes.

In evaluating the role of herbaria in conservation planning, it is pertinent to consider recent insights from the field. According to the recommendation of *Conservation Biology*, prioritizing the reassessment of data-deficient species on the IUCN Red List offers a strategic approach to address gaps in our understanding of species vulnerability and conservation status. Notably, herbaria-based machine learning research can offer a more time- and cost-efficient alternative to the repeated reevaluation of every species. Given the dynamic nature of IUCN categories, which are subject to changes due to habitat fluctuations and human influence, utilizing herbarium-based machine learning approaches could enhance the efficiency of conservation assessments. Reassessment can benefit from the use of herbarium and GIS tools. These resources can aid in evaluating and prioritizing DD (Data Deficient) species using the IUCN Red List of Threatened Species. Conservation efforts

can be directed toward those at highest risk, by identifying DD species most likely to be categorized as threatened (Cazalis et al., 2023). The IUCN Red List is crucial in shaping conservation policies and safeguarding biodiversity.

Herbaria have a unique value compared with modern GIS data stored on various platforms (Amici et al., 2014). Together, these modern tools and herbaria complement the effectiveness of herbaria in ecological data mining and support ecological data (Huettmann & Ickert-Bond, 2017). The integration of herbaria in conservation planning is indispensable, and recent research underscores the potential for herbarium-based machine learning approaches to enhance efficiency in assessing and prioritizing species that require conservation. A nuanced examination of the relationship between herbaria and modern GIS tools enriches the discourse on optimizing data mining strategies in ecological studies.

Impact on Reintroduction Programs, Invasive Species Mitigation, and Habitat Restoration

Herbaria specimens serve a vital function in the reintroduction of endangered species, acting as historical records of distribution that aid in identifying release sites. Their role extends in managing invasive species, where understanding historical occurrence through herbaria data can facilitate effective control measures. Herbaria records contribute to habitat restoration by offering insights into plant species that have historically thrived in given areas.

Effective conservation planning requires interdisciplinary collaboration. Herbarium data and data from other disciplines, such as ecology, genetics, and climatology, offer a comprehensive understanding of ecosystem dynamics. Collaborations enable a holistic approach to conservation, ensuring well-informed decisions.

Practical Examples of Herbarium-Guided Conservation

Numerous practical examples highlight the role of herbarium specimens in guiding conservation efforts. The California Native Plant Society utilized herbarium data to inform policy decisions and prioritize conservation actions (Ward & Howald, 2005). In New Zealand, herbaria records contributed to eradicating invasive species from islands (Hulme, 2020). These examples underscore the impact of herbaria-guided strategies in conservation success. Herbaria collections have emerged as valuable tools in conservation planning. Their historical records enable targeted conservation strategies, inform reintroduction programs, aid in the management of invasive species, and guide habitat restoration efforts. Collaborations with other scientific disciplines amplify the effectiveness of conservation initiatives. Practical examples further demonstrate how herbaria-guided strategies contribute to preserving biodiversity and ensuring the health of ecosystems. Herbaria remain integral to sustainable and informed conservation planning with growing conservation challenges.

TECHNOLOGICAL ADVANCEMENTS AND INNOVATIONS

Integration of Molecular Techniques, GIS, and Machine Learning

Combining molecular techniques with herbaria specimens has opened avenues for research (Besnard et al., 2014). DNA extraction and sequencing from historical samples provide insights into genetic diversity, phylogenetic relationships, and evolutionary processes (Bieker & Martin, 2018). Integration with GIS allows researchers to georeference herbarium specimens, enabling spatial analyses of species distribution changes and habitat preferences; thus, machine learning algorithms aid in species identification, speeding up the taxonomic process (Davis, 2023).

Prospects for Future Research and Technology Development

The future of herbarium-based research is promising. Advances in DNA extraction and sequencing will uncover genetic details from historical specimens. Enhanced GIS capabilities will facilitate more accurate spatial analyses, predicting species responses to environmental changes. Machine learning algorithms will become more refined, enabling faster and more precise species identification.

CHALLENGES, ETHICS, AND COLLABORATION

Challenges and Proposed Solutions

Although technological innovations offer immense potential, challenges persist. DNA degradation in historical specimens is a concern, requiring the development of more efficient extraction methods. Accurately georeferencing the locations of historical collections can be challenging due to imprecise locality descriptions. Machine learning models might face limitations in identifying highly variable species or those lacking sufficient training data. Addressing these challenges demands collaborative efforts from researchers, technologists, and curators.

Technological advancements have propelled herbarium-based research into a new era of possibilities. Integrating molecular techniques, GIS, and machine learning enhances our understanding of biodiversity, species distribution, and ecological dynamics. The field holds exciting prospects for unlocking historical genetic insights, refining spatial analyses, and automating taxonomic processes. By addressing challenges and embracing interdisciplinary collaboration, researchers can harness these innovations to contribute significantly to our knowledge of the ecosystem.

Preservation Quality, Accessibility, and Funding Challenges

Maintaining the preservation quality of herbarium specimens is challenging due to factors like humidity, pests, and storage limitations. Ensuring accessibility to these collections is vital for researchers, but limited digitization and online availability hinder their utility. Additionally, herbaria often face funding constraints, impacting the allocation of resources for maintenance, curation, and digitization.

Ethical Considerations in Collection and Usage

Ethical considerations encompass both the collection and usage of herbarium specimens. Concerns arise around the ecological impact of collecting rare or endangered species, necessitating ethical guidelines for responsible collecting. Furthermore, respectful usage of indigenous traditional knowledge and sacred plants requires careful consideration.

Importance of Inter-Institutional Collaboration

Collaboration among institutions is pivotal for overcoming challenges and maximizing the potential of herbaria. Sharing resources, knowledge, and expertise can facilitate digitization efforts, increase accessibility, and enhance the overall quality of herbaria collections. In addition, collaborative initiatives promote the exchange of best practices and ethical standards.

Recommendations for Maximizing Herbaria Potential

A multipronged approach is recommended to optimize the potential of herbaria. Strengthening funding support is crucial for preservation, curation, and digitization efforts. Embracing technology and digitization can enhance accessibility and broaden the impact of herbaria collections. Developing and adhering to ethical guidelines ensures responsible collection and usage, respecting the environment and cultural sensitivities.

Herbarium-based research encounters challenges related to preservation, accessibility, and ethical considerations. However, these challenges can be overcome through collaborative efforts among institutions, researchers, and stakeholders. By addressing these challenges, advancing technology, and promoting ethical practices, herbaria can continue to play a pivotal role in shaping our understanding of biodiversity, supporting ecological research, and contributing to conservation efforts.

CONCLUSION AND FUTURE DIRECTIONS

Summary of Key Findings

This review of herbarium-based research shows that herbaria collections hold immense scientific value and are essential for understanding biodiversity, ecological changes, and conservation needs. These collections serve as historical records, aiding in ecological studies, taxonomic studies, species distribution analyses, and climate change assessments. However, a crucial consideration for future research involves recognizing and addressing potential inaccuracies in plant identification within herbaria. It is crucial to underscore the importance of taxonomists in mitigating inaccuracies during plant identification and digitization.

Proposed New Ideas and Hypotheses for Future Research

As ecological research advances, herbarium-based investigations present promising opportunities for further exploration and discovery. Integrating genomics with herbaria specimens offers an approach to understanding historical genetic diversity, shedding light on evolutionary patterns and population dynamics. The combination of predictive modeling and GIS can provide robust forecasts of future species distributions, as well as their adaptive response to climatic change. Interdisciplinary studies, with collaboration between ecologists, botanists, climatologists, and data scientists, could provide insights and solutions to complex ecological challenges. These proposed directions highlight the growing significance of herbaria in modern research and suggest fertile ground for inquiries that enhance our understanding of biodiversity and environmental sustainability.

Call to Action for Herbaria Collectors, Researchers, Policymakers, and Conservationists

The sustained advancement of herbarium-based research necessitates a concerted effort across various disciplines. Researchers must strategically emphasize digitizing these collections to enhance accessibility and broaden their use in scientific inquiry. In ecological research, herbaria collectors must facilitate the work of ecologists by making herbaria collections readily available. Obstacles to information sharing and collaboration must be addressed to ensure that they do not impede research progress. Policymakers, recognizing the role that ecological research and herbaria play in shaping conservation strategies, should allocate resources to support these vital areas. Furthermore, conservationists must actively engage with herbaria, integrating historical data into habitat restoration and species protection efforts. These measures underscore a holistic approach to leveraging herbaria collections as dynamic tools for understanding and preserving biodiversity.

Implications for Conservation and Future Endeavors

Herbarium-based research has become an indispensable interdisciplinary avenue, advancing beyond traditional scientific domains. Herbaria, as meticulously curated repositories of historical plant data, serve as vital tools for understanding plant diversity, broader ecological patterns, and the multifaceted relationship between humans and the environment. In areas where ecological unpredictability has become the norm, the importance of herbaria extends beyond the mere cataloging of biodiversity. They are instrumental in developing data-driven conservation strategies that reflect the complexity of our interaction with nature. This intricate connection necessitates a coordinated approach that integrates cutting-edge technologies, fosters interdisciplinary collaboration, and emphasizes ethically responsible practices. The resultant synergy ensures the relevance and preservation of herbaria collections—an undertaking central to the long-term management of global biodiversity.

In summation, the role of herbarium-based research is not confined to academics, but resonates with the broader societal commitment to safeguarding the delicate balance of life on Earth. The insights from this field are integral to our collective understanding of and responsibility for rich biological

heritage. This convergence of science, ethics, and stewardship exemplifies a forward-thinking approach to conservation, underscoring the need for continued exploration and sound management practices. It reminds us of our enduring obligation to align research with broader conservation imperatives, paving the way for a sustainable future.

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