Received: 13 January 2025 | Revised: 12 May 2025 | Accepted: 30 May 2025
DOI: 10.1002/ppp3.70078

OPINION

Plants People Planet PPP Open Access

Life after herbarium digitisation: Physical and digital collections, curation and use

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Funding information
FAPERJ; European Union's Horizon Europe Research and Innovation Programme, Grant/Award Number: 101059592; Swedish Foundation for Strategic Environmental Research MISTRA; CNPq; Royal Botanic Garden Kew Development; Swedish Research Council, Grant/Award Number: 2019-05191

Societal Impact Statement
Collections of dried plant specimens (herbaria) provide an invaluable resource for the study of many areas of scientific interest and conservation globally. Digitisation increases access to specimens and metadata, enabling efficient use across a broad spectrum of research. The value of physical specimens is enhanced by digitisation, but these specimens remain fundamental for the study of traits not yet captured digitally. We investigate the requirements for physical access and the curation and facilities needed to maximise specimen use and value. We present recommendations to ensure that specimens and data are both fully accessible to support research into global challenges.

Summary
Herbarium management has traditionally focused on providing direct access to the physical specimens, but this scope must now expand to also embrace digital collections. Advances in technologies such as artificial intelligence and high-throughput genomics are increasing the amount of information that can be extracted from specimens, and it is becoming commonplace to provide digital access to specimen images and collection metadata. These developments are facilitating the use of herbarium collections to

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inform conservation planning and in studies plant and fungal taxonomy, distribution and evolution. This paper examines how herbaria are transitioning from physical specimen-centric collection management practices to increasingly digitised curation, and the effects that digital availability of data are having on demands for physical access. We provide a set of recommendations to institutions holding herbarium collections. We emphasise the critical importance of further digitising herbaria of all sizes; the need to ensure that historical inequalities in deposition of specimens are not perpetuated; and that the capacity to utilise new technologies must be further developed, especially in biodiverse regions from which most herbarium collections are derived.

To improve access to collection data, herbarium managers need to more rigorously adopt community-agreed data standards, and more strongly support open access platforms such as the Global Biodiversity Information Facility either directly or through regional coalitions. As digitisation and open data access increase, herbaria will need to offer users with seamless hybrid access to physical and digital records while continuing to develop their collections to advance research and conservation.

KEYWORDS
collection management, data standards, equity, herbaria, infrastructure, specimens

1 | INTRODUCTION

1.1 | Digitisation

Digitising natural history collections increases the accessibility and interconnectedness of information required to provide solutions to global challenges, from biodiversity loss to climate change and food insecurity. The extended specimen – the specimen linked to a network of related data including collection metadata, images, scans, recordings and DNA sequence information – greatly enhances the relevance of specimen data for interdisciplinary and applied studies from science and conservation to arts and humanities (Bakker et al., 2020; Canteiro et al., 2019; Davis, 2023; Lendemer et al., 2020). Although much has been written concerning digitisation, this article focuses on herbarium management and the challenges of balancing physical and digital collection management to ensure that herbaria inform the broadest range of scientific and environmental research.

The last decade has seen extensive digitisation of botanical collections by institutions (e.g., De Smedt et al., 2024; Le Bras et al., 2017), and by countries where institutions are working together to explore efficiencies at scale through initiatives such as DiSSCo, Reflora, Canadensys and iDigBio (Pinheiro et al., 2024; Sinou et al., 2019; Smith et al., 2022; Thiers, 2024). The accessibility of digitised herbarium specimens is increasing through these efforts (Figure 1). Thiers (2025) suggested on the basis of *Index Herbariorum* records, that the estimated number of herbarium specimens in the herbaria listed was 402,267,414. However, current Global Biodiversity Information Facility (GBIF) data represent just over 130 million preserved specimens of plants and fungi. Assuming plants and fungi represent the main contents of herbaria, it would suggest that only 33% of herbarium material is represented in GBIF (30% plant and 3% of fungal preserved specimens). Considering smaller herbaria may not be recorded in *Index Herbariorum*, the actual proportion may be lower still. The percentage of records with images present in GBIF is also much lower for most groups, with vascular plants having the highest proportion of records with images (see Table 1).

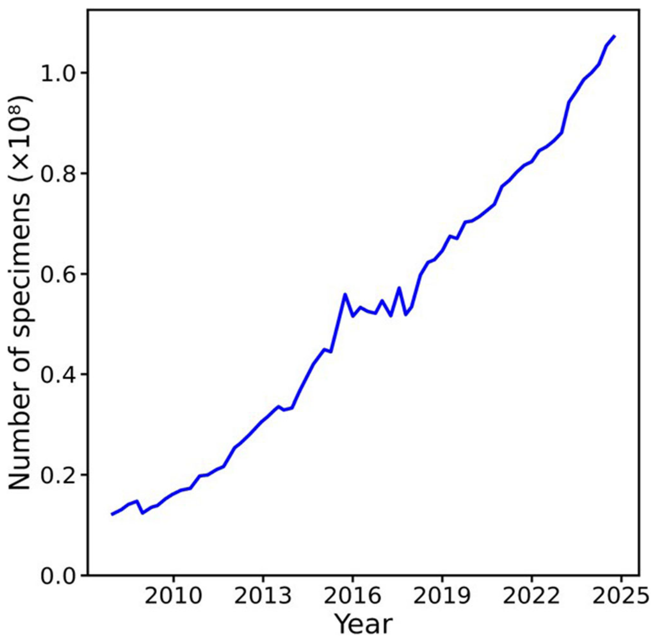

FIGURE 1 The number of specimens of vascular plants in GBIF from 2007-12-19 to 2024-10-01. GBIF -Data trends (gbif.org) accessed 17 Oct 2024. Over 95% of the plant specimens are vascular plants.

TABLE 1 Number of total records, preserved specimens and number of images of groups most commonly found in herbaria in GBIF (https://www.gbif.org, accessed 2 May 2025). Only plant and fungal groups with more than 0.5 million preserved specimens are shown. Specimens can have more than one image, which means that the percentage of specimens with images is lower than the number given.

Number	All plants	Vascular plants (Tracheophyta)	Bryophyta	Marchantiophyta	Rhodophyta	Chlorophyta	Fungi
Records in GBIF	516,906,861	490,748,627	16,394,570	3,725,701	2,749,481	1,783,035	44,294,788
Preserved specimens	121,967,966	111,498,267	6,127,613	1,716,639	1,430,419	563,455	12,694,578
Images of preserved specimens	55,270,633	52,377,814	1,448,157	345,869	527,234	243,462	2,489,183
Image number as a percentage of preserved specimen number	45%	47%	24%	20%	37%	43%	20%
GBIF preserved specimen number as a percentage of the total number of herbarium specimens (402,267,414) estimated by Thiers (2025)	30.3%	27.7%	1.5%	0.4%	0.4%	0.1%	3.2%

Observations by citizen scientists are also used to record biodiversity, and herbarium specimens will increasingly be used alongside citizen science data based on photographic records in identification apps such as iNaturalist (Calvente et al., 2023; Mesaglio et al., 2023). However, in addition to allowing sampling of physical material, herbarium specimens can provide more taxonomic, phylogenetic and functional diversity data than observations (Eckert et al., 2024).

Despite progress, digitisation of un-digitised herbaria is still greatly needed, particularly in many low-income biodiverse countries where the necessary funds have not yet been secured. The current data mobilised from specimens also shows a strong bias towards those in collections in the Global North irrespective of where they were collected (Davis, 2023; Park et al., 2023; Paton et al., 2020). These factors have led to calls to better resource collection infrastructure, including digitisation in countries where the specimens originated (Antonelli et al., 2025; Johnson et al., 2023; Kaiser et al., 2023; Park et al., 2023).

1.2 | Growing use of artificial intelligence and high-throughput sequencing

Herbaria are increasingly using technologies such as artificial intelligence and high-throughput sequencing to enhance and increase the use of specimens for environmental, evolutionary and other studies. Application of AI to herbarium images has ranged from classification (identifying the species represented in the specimen), to digitisation and transcription tasks (identifying regions of the specimen image containing text and extracting this for further processing; Weaver et al., 2023) to trait measurement, e.g., leaf dimensions (Weaver et al., 2020; Wilde et al., 2023, Guo et al., 2024); and phenology based on leaf, bud, flower or fruiting data extracted from label and specimen data (Goëau et al., 2022).

GBIF post monthly snapshots of specimen metadata conforming to community data standards and harvested into their data portal in major cloud providers (GBIF, 2025), enabling researchers to bring their ideas to the data. The same is not true for images – researchers and AI developers have to rely upon defined datasets, e.g., the herbarium half Earth challenge (de Lutio et. al., 2022), or laboriously visit each provider and negotiate with the many different ways that they choose to serve up images, with associated data access costs. Phenology data and annotations, important in understanding seasonal changes over time, are another class of data where the lack of supported standards and a place to deposit the data results in researchers having to search through images and specimens to extract this information (e.g. Austin et al., 2024; Pearson et al., 2020). A functional, shared, open infrastructure providing world-wide access to interoperable specimen data and facilitating greater use of technologies such as artificial intelligence as envisaged by Groom et al. (2023), is still some way off. The lack of such an infrastructure perpetuates the global inequalities in specimen access and capacity for data analysis.

Advances in technology have enabled much more efficient extraction of genomic data from specimens (Burbano & Gutaker, 2023; Kates et al., 2024; Zuntini et al., 2024). Currently, around 215,000 vascular plant species have data in the European Nucleotide Archive, representing just over 60% of the estimated total species number of approximately 343,000 (Govaerts et al., 2021). However, only 11% of these (23,761) species had recorded voucher specimens (ENA, 2024). Many of these are likely to have vouchers, but this information is often missing from sequence databases. Thus, evidence of accurate species identification and detailed locality information is missing, making sequence data disassociated from spatial data.

1.3 | Balancing digital and physical collection management

Digital specimens present great opportunities for research and for collection management. Specimen metadata can be captured digitally at the time of collection, associated with other field data and made accessible to other researchers and interlinked to other relevant information quickly. Specimen names can be automatically updated when nomenclature changes at minimal cost, and new workflows can allow analysis even before mounting and incorporation into a collection.

However, access to physical specimens will still be required to study characters not yet accessible digitally, such as molecular characters not previously assayed, anatomical and morphological traits or floral parts where study requires dissection. Research and curation activities interacting with both physical and digital specimens can support an integrated approach to managing both types of collections in effective and accessible ways.

2 | WORKSHOP

A workshop was convened virtually involving 40 herbarium-based researchers and curators from 20 countries to discuss the management and use of physical herbarium specimens in the context of increasing digitisation. The workshop was coordinated by The Royal Botanic Gardens, Kew, who also ran a similar but internal workshop asking the same questions with 20 participants. Both workshops were centred around a set of questions detailed below, and notes captured on a Miro board (miro.com). Initial results were written up and made available online to all participants for further comment. Participants were invited to contribute to the preparation of a manuscript, and the authors subsequently developed this article. This paper summarises the findings of these workshops and presents recommendations resulting from ensuing discussion. Although focused on herbaria, and in particular vascular plant collections, we hope that the conclusions will be of value to any natural science collection manager or user. Vascular plant collections provide an appropriate context to explore continuing physical use as they are one of the most digitised natural science collections (Groom et al., 2023; Table 1). Non-vascular plant specimens and fungi are likely to need more physical analyses, as many of the features of the specimens which allow accurate identification are microscopic.

This article addresses the future role of physical collections in enabling research by examining the following questions: In light of increased digitisation, what research will still require physical access? What infrastructure is required for research which has to be conducted with the physical collection? What physical and digital curation activities will be required to support research? We conclude with recommendations for progressing from current physical specimen-centric herbarium management practices to a situation where management of physical and digital curation is balanced to maximise the use and impact of collections and collection data in advancing fundamental science and tackling global environmental and social challenges.

3 | WORKSHOP RESULTS

3.1 | What research will still require physical access?

3.1.1 | Taxonomy and morphology

Plant taxonomy involves the study and comparison of morphological and other characteristics to accurately classify, identify and differentiate plant species. Taxonomy has consistently embraced and applied new technologies to enhance our understanding of species boundaries and relationships (Simpson, 2019). The study and sorting of herbarium specimens is essential to create or test hypotheses of species circumscription. The citation of physical specimens as material belonging to a particular species or as type specimens is an important part of the taxonomic process helping define the species. Access to digital specimens can greatly facilitate this process, especially if the work involves comparison of geographically dispersed specimens.

Physical herbarium specimens have been used in ways early collectors could not originally envisage. While high-resolution digitised images can provide much of the necessary information for taxonomists to do their work (Wood et al., 2015), researchers frequently still need to examine physical specimens in order to observe details that might not be visible even in the highest-quality digital specimens (e.g., microscopic or anatomical characters, characters that are inside flowers or other structures, or that are on the lower surfaces of the specimen that are not visible when imaged or phytochemical or DNA characters. Barrett et al. (2024) assessed the proportion of characters required to define new species in a group of closely related peas of the *Pultenaea setulosa* species complex that could be measured from digital specimens, finding that about two-thirds of characters could be measured, but progress was slower as digital images were more difficult to interpret accurately. The other third of characters were either too small or hidden from view without dissection or hydration of the dried specimens. Typification projects, however, such as assessing the application of names in the pantropical *Hibiscus* section *Furcaria*, were able to heavily rely on digital images, as in most cases, the study did not require re-examination of microscopic characters (Barrett et al., 2025). The need for access to physical specimens is likely to be greater in taxa such as Bryophytes, where identification routinely requires microscopy.

Many plant families require detailed microscopic examination, and large families such as orchids (Orchidaceae), grasses (Poaceae) and Compositae (Asteraceae), often require physical dissection for identification. Dissecting and imaging flowers on accession of all specimens arriving may be possible, but is unlikely to be cost-effective in the near future in comparison with targeted dissection to answer particular research questions. The cost of secure storage of very high resolution images, and the environmental impact of cloud storage (Kumar & Buyya, 2012) are likely to influence decisions around image resolution in the future, although extensive efforts are underway globally to make information storage and processing more effective and less environmentally damaging. Routine specimen imaging will be useful to identify specimens of interest for further study, and it will allow secondary, more detailed images when most needed, enabling strategic use of available resources.

In conclusion, we expect that physical examination, which involves repeated comparison of different characters over subsets of specimens, is likely to be the most efficient research process over the short to medium term. However, as tools such as iCurate https://www.nybg.org/files/scientists/dlittle/icurate/,LeafMachine 2 (Weaver & Smith, 2023) and others mature and become increasingly part of the curricula in taxonomic training alongside the expanding use of AI, digital assets are likely to play an increasingly significant role in species identifications and various other taxonomic projects. Many herbaria are exploring the use of AI, Missouri Botanical Garden providing a recent example (Missouri Botanical Garden, 2025).

3.1.2 | Genomic studies

The accessibility of modern high-throughput techniques is facilitating an increase both in sampling (Davis et al., 2025) and the diversity of types of study (Burbano & Gutaker, 2023). Herbarium material allows genomic studies of the plants and any associated microbiomes, pathogens and parasites, including accessing past ecological interactions with arthropod communities (Stothut et al., 2024). As noted above, many species have still to be sampled and sequenced, and for unsampled species access to fresh or preserved material may not be available or may not represent a cost-effective option. Herbarium collections are now being seen as a long-term DNA tissue repository, and demand for sampling needs to be carefully managed (Davis et al., 2025). Routine digitisation, particularly imaging, also allows identification of specimens for genomic analysis of relationships or population structure. Such sampling and sequencing could become part of the accessioning process, with each specimen linked to its image and genomic sequence. However, as discussed further below, curatorial staff are already taking on additional digital curation tasks, limiting the amount of physical processing that can be done without additional resources. However, it may be possible at the pre- accession phase to label material most suitable for genomic sampling in the future.

3.1.3 | Trait investigation

Herbarium specimens are often sampled for research under a range of techniques, or studies for which data are not available on herbarium images, including anatomy, biochemistry, including metabolites, stable isotopes, air pollutants, spectral reflection or absorption and multi-dimensional traits such as leaf thickness (Heberling, 2022). The use of biochemical markers in taxonomy has been key to understanding the relationships among plant groups, and herbaria have long been acknowledged as a key source of phytochemical data (Hegnauer, 1986). Infrared spectroscopy is now being used for rapid tree species identification (Lang et al., 2015) and to investigate chemical composition of specimens (Barnes et al., 2023) giving new insights into species-specific, temporal and spatial variation in chemistry.

Even though techniques for extraction and analysis are likely to improve over time and costs per specimen (excluding labour) will likely decease, it is unlikely that data gathering for all such analyses can be routinely conducted on accessioning. A trial of a particular group of plant species where all specimens were, for example, chemically studied may help demonstrate the value of this data and help generate funding for such targeted investigation.

3.1.4 | Humanities research

Physical access to herbarium specimens is important for researching collections with regard to cultural heritage, the history of science and provenance research. Such studies include the specimen itself, groups of specimens by the same collector, and also physical attributes such as the preparation method, the arrangement of the specimens (in volumes) or characteristics of the material. Also, physical specimens as cultural items remain important and have roles to play in examining, for example, colonial behaviour and proper accreditation of indigenous people (Clarke, 2008; Taylor & Huxley, 2020; Vaughan et al., 2024) and other aspects of exploring the historic and cultural context of the collection. The Greenbelt Indigenous Botanical Survey project in southern Ontario is an example of how an indigenous-led contemporary survey, and collection can provide mechanisms to investigate indigenous land management, oral history and the cultural relationship with plants (https://gibsurvey.ca/about).

Routine (and mass) digitisation, including data capture, holds great potential but is influenced by value-driven decisions such as throughput (e.g. Kaiser et al., 2023). Consequently, the digitisation of herbarium specimens (and indeed other collection objects) may not capture all potentially relevant information present in or on the physical object. In addition to information that has not yet been identified as relevant in research, significant portions of herbarium specimens are frequently omitted from current digitisation initiatives. These include the reverse sides of labels and mounting papers as well as intrinsic characteristics of the material such as watermarks. The latter can be crucial for studying and contextualising historical herbarium specimens, as evidenced by the work of Offerhaus et al. (2021).

In a considerable number of cases, contextualisation is the method by which historical herbarium specimens that have survived without the information necessary for botanical study can be made available for research purposes. The place and date of discovery can only be determined through a process of meticulous detective work, involving the study of duplicates or the analysis of manuscripts, mounting techniques and accompanying archival material. Interdisciplinary research, such as that currently being carried out on Hans Sloane's famous herbarium of more than 120,000 individual specimens (Scott et al., 2025) and on 18th-century specimens relating to the Christian denomination of the Moravian Church (Ehrlacher et al., 2024; Ruhland, 2021; Wagner et al., 2023), highlights the importance of physical objects for the history of science and the need for close access to the objects and all their layers of information due to their complex histories of composition and acquisition. The authors of those studies emphasise the risk of losing the contextual and historical dimensions of objects through the loss of materiality when historical collections are accessed exclusively in a digital format. Continuing the traditional practice of inter-institutional herbarium specimen loans can provide access to physical material. While loans continue to be useful, the ability to loan is can be limited by how delicate and fragile a specimen is.

3.1.5 | Training and collaboration

Handling specimens and specimen data, sampling and understanding of basic collection management is an important element of training the next generation of plant scientists. Taxonomy is often collaborative, involving joint specimen study and discussion. Training and supervision may require coordinated access to particular collections by the student or visitor, researcher and curator at the same time. Discussion based on physical and digital material is an important element of all of these collaborative activities. As AI and other technological tools continue to evolve, training courses should incorporate these advances into their curricula, which in turn requires continuous professional development of teaching staff and scientists.

Herbaria continuously expand through acquisition of new specimens, including duplicates that are widely distributed among various institutions, particularly to fill gaps in existing biodiversity knowledge (Ondo et al., 2024). Future collections will ensure the vouchering of observations, experiments and analyses can continue. These collections are vital to provide a resource for future generations to understand changes in the environment and biological diversity (Antonelli et al., 2025; Heberling, 2022).

3.2 | What infrastructure or facilities are required for research which has to be conducted in the herbarium?

To conduct research in a herbarium, several specialised infrastructures and facilities are essential to support both physical and digital access to collections. These spaces must cater to a variety of research and curatorial activities, specimen preparation and collaboration; they are not, and should never become, simply storage facilities (Thiers, 2024). Physical access to working areas close to the collection to allow study of large amounts of material is important. Specimens should ideally stay on site to reduce damage and allow several members of a team or visiting collaborators to study them, though loans provide an option to enable collaboration and study by those unable to visit.

Given the vast number of digital specimens available, research facilities now need to enable researchers to study the physical and digital specimens in an integrated workstation. The use of the International Image Interoperability Framework (IIIF) can bring specimen images from herbaria across the world into a single online viewer for comparison (De Smedt et al., 2024; Hyam, 2019). This can then be viewed alongside the physical specimens to create a workspace which fully benefits from the digitisation of collections. Allowing access to institutional databases which allow visiting researchers to add additional data such as identifications to the existing digital catalogue will benefit a wide range of users. For example, the Herbarium of the Le Muséum National d'Histoire Naturelle in Paris allows visiting researchers to add identifications into the institutional database and print out determination slips for the specimens, making the process very efficient and maximising the expertise of the visitor to improve the value of the collection, physically and digitally. Such integrated workstations realise the 'global meta-herbarium' (Davis, 2023), offering opportunities for redress and to promote equitable accessibility, considering the historical legacy of colonialism and the uneven deposition of specimens, which is biassed against biodiversity-rich countries. Herbarium managers are increasingly having to balance remote demands such as for high-resolution images and samples of specimens for analysis. These are important functions which will compete for curation resource. Where possible Herbaria should try and resource such requests, but may need to consider charging or limiting the amount of material sent to cover costs, asking for co-authorship or asking to be included in research grants resourcing access (Davis et al., 2025).

3.3 | Key infrastructure requirements to facilitate access to physical herbarium specimens and research include

3.3.1 | Spaces and facilities for physical access and examination

Examination and study areas: Sufficient space is necessary for researchers to comfortably examine specimens. These areas should be equipped with proper lighting and surfaces for specimen handling and detailed observation.

Microscopy and dissection facilities: Providing appropriate microscopes and tools for specimen dissection is critical for detailed taxonomic, morphological and anatomical studies.

Curatorial and specimen preparation areas: Dedicated areas for curatorial work and sample preparation are crucial. This includes facilities and controlled environments for pressing, drying, storing, labelling, pre-mounting and mounting specimens before being frozen and integrated into the correct place in the collections (Davies et al., 2023). Facilities for sample preparation and packaging to ensure safe preservation and transport of specimens are required, especially for research that involves loans and exchanges. Curatorial activities such as preparation and incorporation, loan selection and answering enquiries require close adjacency to the specimens. While material for loan can often be selected by curatorial staff, more technical sampling or study might require input from the researcher who has experience of the techniques involved and can choose the appropriate material for the work. The most appropriate material to sample will often be held within a capsule on the sheet and not imaged. In addition, close inspection may reveal that the specimen is unsuitable, e.g., parts too heavily glued or dried with the aid of alcohol. Delicate historical specimens may need to be protected from sampling unless there is strong scientific justification, and other specimens cannot serve the research purpose. Specimens may also be covered by access and benefit sharing agreements with provider countries, which prohibit sampling. If large-scale sampling is needed, the researcher might need to provide their own labour. However, sampling policies of the herbarium must be followed. Standardisation within an institution and training of new staff is important as sampling demand increases. Procedures differ between herbaria, meaning training is also essential to understand these differences when working across institutions.

Laboratory facilities: Laboratories equipped for preparing and preserving samples of specimens for research (e.g. molecular or chemical samples) or microscope work are necessary.

Spirit collections (wet collections) also require laboratory-like conditions, with a controlled environment for maintaining temperature and humidity and regular air exchange. Preparation of material and study also requires measures to ensure the safety of those working in the collection (Neumann et al., 2022).

3.3.2 | Digital and literature access

Internet access: Reliable internet access throughout the herbarium, including collection and adjacent office spaces, is essential for checking specimen data by accessing digital databases, literature, conducting online research and many curatorial practices.

Access to literature: Taxonomic research requires access to both digital and non-digitised literature, such as modern Floras and copyrighted works. Some literature is hidden behind a paywall, rendering it inaccessible to many (Nicolson et al., 2023). Ensuring the availability of these resources is key for supporting research. The *Disentis Roadmap* sets out some of the issues related to restricted biodiversity knowledge and the need to publish biodiversity using FAIR principles (https://www.bouchoutdeclaration.org/background-2024/).

3.3.3 | Advanced imaging technology

Imaging facilities: Detailed imaging technologies like 3D stereo imaging, electron microscopy, multi- and hyperspectral imaging or access to CT scanning may be necessary for certain studies requiring in-depth visual analysis of plant structures or for preserving irreplaceable specimens (e.g., historic) through non-invasive methods (e.g., CT scanning) though more complex equipment may be available through off-site specialist providers.

Imaging infrastructure: As digitisation becomes more prominent, robust imaging facilities are crucial for creating high-resolution images of specimens. There are now low-cost solutions suitable for any small or medium-sized herbarium (Takano et al., 2019). This allows remote access to plant material, reducing the need for physical visits while expanding accessibility to global researchers. Digitisation of incoming material and facilities to update the digital catalogue will remain important.

Imaging and sampling on demand: Developing well-resourced imaging or sampling services that can fulfil requests on-demand would make collections more accessible, especially to remote researchers. This service can potentially reduce the need for physical visits by providing high-quality digital alternatives or physical samples. However, this virtual consultation of the collection will often require effort from the collection staff to answer enquiries and service demand for sampling or imaging and can impact on institutional capacity for collection management (Hardy et al., 2020).

3.3.4 | Specimen management and pest control

Specimen accessioning: Appropriate spaces to sort and manage incoming and outgoing specimens are required. This includes areas for the initial assessment of specimens, storage during the curation process and preparation for loans or sampling requests.

Pest-free housing: Specimens must be housed in a pest-free environment to ensure their long-term preservation. This can be especially difficult in biodiversity-rich areas such as the tropics, where diversity of pests, alongside high temperatures and humidity, make care for the collections far more challenging, especially due to recent limitations of fumigation and mercuric chloride poisoning due to concerns about human health (Lee et al., 2021). Controlled conditions are vital to maintain the quality of the collection as it moves through different stages of the curation workflow. Other pest control measures are also necessary, such as monitoring and decontamination of incoming material by freezing or other treatment (Davies et al., 2023).

3.3.5 | Visitor amenities to support specimen study

A reception and orientation area: a staffed reception and orientation area for welcoming visitors and explaining the purpose of the herbarium is important. This area can also serve for deliveries and inquiries.

Social spaces: Spaces designed such as tea/coffee rooms or shared lunch areas for social interactions are desirable to promote collaboration, scientific discussions and overall well-being for staff, researchers and visitors.

Collaborative spaces: Spaces that encourage scientific discussion and teamwork among researchers, curators and visitors are essential for fostering collaboration and scientific discourse, for example, rooms with large layout tables to discuss specimens or seminar rooms to discuss results.

Quiet study and training areas: Quiet spaces for study, training and education are necessary to support researchers and students working within the herbarium. Many of the access requirements, facilities and support necessary to support research are also needed for education and training.

Visitor needs: Visitors to the collection will need local accommodation and transport to the herbarium. More detailed accounts of visitor requirements are detailed by Puglisi and Paton (2023).

3.3.6 | Equity in access and collaborative science

Promoting team science: Beyond just preserving collections, herbaria should aim to promote equitable access to research facilities. As highlighted by Thiers (2024), increasing digitisation and access to tools for remote analysis can address infrastructure inequities that limit participation in botanical research.

This combination of physical and digital infrastructure, along with spaces that promote collaboration, is essential to the functioning of a modern herbarium, balancing the need for both on-site research and global digital access to plant specimens.

3.4 | What curation activities will be needed to support research?

Digitisation will result in new or increased practices such as updating the digital catalogue with new accessions, updated identifications or adding additional information to maximise the use of collections such as georeferenced data, information about collector trips and exact localities or information on the communities that supported the collection. Curation of the digital collection will become increasingly important and make some activities easier, such as checking restrictions of use attached to a particular specimen by transfer agreements and national laws or the choice of material for loan or sample preparation. Sharing identifications and other annotations from duplicate specimens across collections will also make curation more efficient, for example, updated identifications or knowledge that a duplicate has already been sequenced in another institution will be more easily shared. Linking specimen data across collections and to other data resources is already possible (Güntsch et al., 2021), but in the future, further data standards will need to be developed and adopted to maximise the benefits that such linked open data can provide (Groom et al., 2023; Lannom et al., 2020).

Prioritised physical interventions within the collection to facilitate use will be required. The curatorial functions that increase access to the collections include: naming, rearranging the collection where necessary to facilitate physical access (for example, re-identification ensuring specimens of the same species are physically together facilitating taxonomic research and sampling). For example, some species in *Coleus* (Lamiaceae) are held in three or more places in many herbaria due to complex synonymy, making it difficult to find material physically (Paton et al., 2020). Staff will also support formal and informal training and provide guidance and orientation to new herbarium users. The increased needs of digital curation will reduce time available for necessary physical curation. Digitisation projects need to consider the resourcing of ongoing requirements of physical and digital curation. Digitisation will make some physical curation tasks easier, but curators and researchers have to maintain both the physical and digital collection, rather than just the physical, or just digital (De Smedt et al., 2024; Figure 2), meaning staffing needs post-digitisation may be larger than before it, rather than the opposite. Maintaining records of visitors and activities such sampling or digitisation on demand, should be recorded to demonstrate the use of the physical collection and to support requests for additional funding.

4 | DISCUSSION

Herbaria are not just storage facilities providing safe storage for botanical information extracted the moment specimens are collected, but are open repositories that enable specimen use and research for many purposes beyond the original reason for their collection. Herbaria are making good use of technology to increase access and use of their collections. As herbaria invest in the creation and curation of digital collections which previously did not exist, further resources are likely to be needed to support this major expansion. We hope that the following recommendations may help balance stewardship of physical and digital collections to maximise their use and impact in solving global challenges.

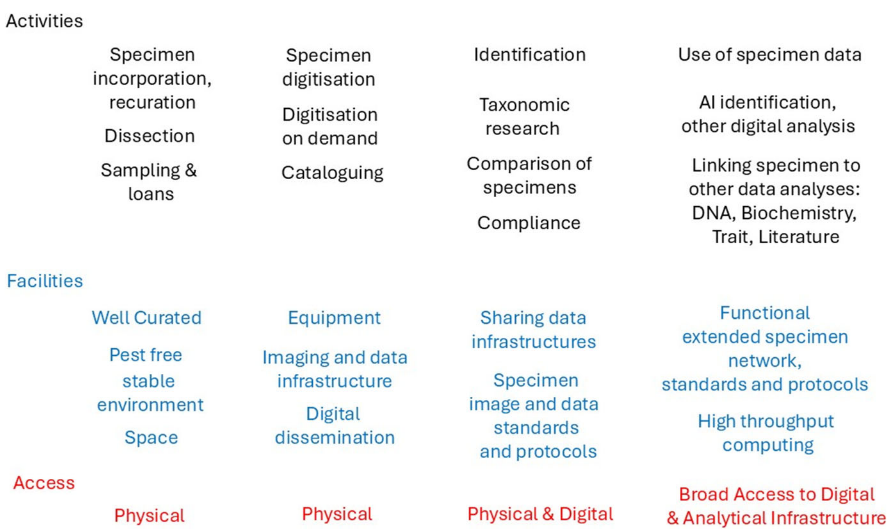

FIGURE 2 Examples of the relationships between activities of the herbarium and the facilities or requirements, and type of access required. Columns relate activity with relevant facilities and access requirements. The more physical activities are on the left, the more digital on the right. A linear, left-to-right relationship is not intended. Digital analyses may result in the need for further physical access, and digital discovery can result in the need to study the physical specimen.

4.1 | Recommendations

1. Digitisation of herbaria is vital, not only for large herbaria in high-income countries but for all herbaria (Kersey & Antonelli, 2023). Digitisation of herbaria in biodiverse low-income countries is often under-resourced, but these collections hold crucial information for plant research and conservation (e.g., Delves et al., 2024). Digitisation of such collections needs to be supported by funders and institutional management to ensure researchers can benefit from the current documentation of biodiversity now and in the future (Antonelli et al., 2025; Johnson et al., 2023; Park et al., 2023). The GBIF Biodiversity Information for Development programme is one example of effectively increasing access to collection and other biodiversity information for research and policy support (Raymond et al. 2019).
2. The inequalities in the deposition of historical specimens are enforced by the lack of infrastructure in low- and middle-income countries to undertake mass digitisation projects and fully benefit from the advances in AI and genomic technologies. Funding for digitisation and greater access to analytical technologies is necessary to build capacity and further promote biodiversity research and conservation in biodiverse regions. Herbaria need to collaborate to provide access to specimens, samples and infrastructures to use the digital data created. Open infrastructures which enable analysis of large amounts of image and sequence data from any country need to be developed (Groom et al., 2023). Perhaps the multilateral fund to facilitate benefit sharing arising from the use of digital sequence information, known as the Cali Fund, established by the Conference of the Parties of the Convention on Biological Diversity (UNEP, 2024), could be used to build capacity and infrastructure in biodiverse countries. This could enable digitisation of collections and provide greater access to technologies such as AI and high-throughput sequencing development, so that data from national collections can be used to better address national priorities. As AI is used increasingly, it will be necessary to capture metadata about how the digitisation is done. For example, was transcription manual or automated, what AI model was used to extract data, how was the specimen identified or georeferenced. Documentation of the pipelines to allow an understanding of biases and error sources will be increasingly important. In the absence of creative strategies to promote access to specimens and associated information, the digitisation enterprise is likely to perpetuate the colonial legacy and resulting disparities, hampering realisation of the full potential of collections and related research.
3. Institutions and their funders should support the Global Biodiversity Information Facility (https://www.gbif.org/), including uploading data either directly or through national nodes such as Canadensys as mentioned previously, to facilitate access to data and specimens (Johnson et al., 2023; Paton et al., 2020). Currently, not all data from other resources are mirrored to GBIF. Funding mechanisms such as the GBIF Capacity enhancement programme can assist with such issues (https://www.gbif.org/programme/82219/capacity-enhancement-support-programme).
4. Herbaria should support the development and adoption of standards, for example, the use of Darwin Core, standard identifiers and IIIF image format to facilitate linkage of specimen data and images to other data (De Smedt et al., 2024; Güntsch et al., 2021). Existing data standards are not always applied correctly, and institutions and repositories both have a role in providing training and feedback to improve data quality. Genomic databases should ensure that unique specimen identifiers and metadata to ensure clarity and accuracy in referencing the source specimen are included in the metadata of sequences derived from specimens
5. The leadership and funders of institutions responsible for herbaria that are undertaking digitisation or planning to do so should consider the resourcing required to maintain the digital and physical collection post-digitisation. Both should be maintained to allow appropriate access to support research and to protect the collections from physical and digital threats, from the risk of fire and pests to cyber attacks (CSIDB, 2023) and the use of data for purposes not authorised by the material providers. Institutions will need to support staff and understand the increase in workload for those having to maintain the updates of both physical and digital specimens. Realistic reporting helps other herbaria understand the responsibility of managing both physical and digital collections, what staffing and training is needed to keep collections curated to a good standard, to make them searchable and useable. Moving to a balance of digital and physical collection management will require a change in workflows, with a period of trial and error until optimal workflows are developed.
6. Herbaria need to continue to collect physical specimens to understand plant and fungal diversity today and provide research baseline data for the future. The distribution of duplicates should be encouraged where possible to mitigate the risk of damage and to enable broader access, taking into account relevant laws on access to genetic resources and benefit sharing.
7. While digitisation makes images of specimens widely available, herbaria need to provide access to physical specimens to provide material for physical comparison, destructive sampling or microscopic analysis. It is, however, crucial that sampling is done in ethical and considerate ways (Davis et al., 2025).
8. Digital collections also need curation so that the data remain accessible and corrections or additions to specimen metadata are disseminated. Georeferencing can provide additional value to the digital record increasing its use in modelling and other analyses of distribution. New tools, automation and crowdsourcing can be effective mechanisms to georeference large numbers of specimens (Sparrius et al., 2024). Physically separated specimens in different herbaria can also be compared informatically by locality or collector, and data from can be shared between connected specimens (Nicolson et al., 2018). Herbaria will need to invest in such tools, combining AI with both metadata and digitised specimen

images offers significant potential for improved accuracy and efficiency in specimen identification.

9. Herbaria should collaborate closely to ensure efficiency, including sharing label and annotation data for duplicate specimens and coordinating collecting and sampling strategies and methods. Collaborative training and reciprocal visits can provide opportunities to disseminate lessons learned and further develop best practice. As an example, the Council of Heads of Australian Herbaria financially supports an exchange program between local herbaria for curators and researchers. Herbaria should work together to support partners in under-collected areas to build collections and infrastructure (Antonelli et al., 2025). For example, the Brazilian Reflora project deployed a mobile digitisation workstation to partner herbaria across Brazil, resulting in the digitisation of nearly 5 million specimens for the Reflora Virtual Herbarium including the sharing of specimen data and images from Muséum National d'Histoire Naturelle, Paris and the Royal Botanic Gardens Kew (Pinheiro et al., 2024). This model could be replicated in other countries.

   As Thiers (2024) recommends, herbaria will also need to be more proactive in forming collaborative relationships with broader science and conservation initiatives, as well as the general public through outreach activities, to demonstrate the value of physical and digital collections. For example, active collaboration in research grant proposals could provide resources to sample collections (Davis et al., 2025), georeference specimens or explore the use of AI to more efficiently identify specimens or develop novel ways to use specimen data to assist conservation planning.
10. Technology will drive changes in the ways we use herbarium collections, probably providing tools we have not thought about yet. Herbaria will need more flexible infrastructures to accommodate rapid change

AUTHOR CONTRIBUTIONS

All authors were involved in workshops and subsequent discussions. Alan Paton wrote the first draft with contributions and feedback from Alexandre Antonelli, Alastair Culham, Sofie De Smedt, Quentin Groom, Elspeth Haston, Paul Kersey, Muthama Muasya, Nicky Nicolson, Emily Sessa, Eric Smets, Alex Sumadijaya, Jordan Teisher, Janine Victor, Sarah Wagner and Andrew Young. All authors then contributed additional feedback before the manuscript was finalised by Alan Paton and re-circulated for final approval.

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ACKNOWLEDGEMENTS

The authors thank other participants of the workshops held in May 2023 and Tim Robertson for data related to the Global Biodiversity Information Facility. AA acknowledges financial support from the Swedish Research Council (2019-05191), the Swedish Foundation for Strategic Environmental Research MISTRA (Project BioPath) and RBG Kew Development. QG receives funding from the European Union's Horizon Europe Research and Innovation Programme for the B3 project (ID No 101059592). RCF and DC receive funding from CNPq and FAPERJ. Views and opinions expressed are those of the authors only and do not necessarily reflect those of their organisation or funders.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

CONFLICT OF INTEREST

None declared.

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How to cite this article: Paton, A. J., Ameka, G. K., Antonelli, A., Asase, A., Barrett, R. L., Bogaerts, A., Cardoso, D., Carine, M., Culham, A., Dalimunthe, S. H., Davies, N., De Smedt, S., Demissew, S., Forzza, R. C., Groom, Q., Haston, E. M., Kartonegoro, A., Kersey, P., Larridon, I., … Young, A. (2025). Life after herbarium digitisation: Physical and digital collections, curation and use. *Plants, People, Planet*, 1–13. https://doi.org/10.1002/ppp3.70078