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Standard Paper

Management and publication of scientific data on traditional mycological and lichenological knowledge in Africa

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Abstract

Africa is an important global reservoir for biological, cultural and traditional knowledge about fungi and lichens, which are used as food, medicine and in mythology, among other things. African human populations are undergoing highly significant changes and adaptation processes, which are accompanied by rapid urbanization, meeting with western civilization, high rural migration and the loss of natural ecosystems. Indigenous knowledge is being lost, including that concerning fungi and lichens. Ethnomycology and ethnolichenology provide a diversity of knowledge about beneficial and poisonous fungi and lichens, and give insights into their sociological impact on human behaviour and use. Here we present a working and publishing environment established with the Diversity Workbench software in line with national and international initiatives for FAIR guided provision of research data. The database application called 'EthnoMycAfrica' contains published ethnomycological and ethnolichenological information from Africa. The content is created and curated by team partners from Central, East, West, North and Southern Africa. Data entry is performed both online and offline, optionally via a mobile device. Currently, the system with the tools DiversityDescriptions and DiversityNaviKey contains a total of 1350 well-structured and freely and openly accessible data records. EthnoMycAfrica is the first database with a data schema, standard descriptors and data content created mainly by African scholars. The data can be useful for researchers, students, conservationists, policy makers, and others. It will also provide a basis for facilitating hypothesis generation and meta-analysis.

Keywords: Diversity Workbench; ethnolichenology; ethnomycology; traditional knowledge

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Introduction

Ethnomycology, including ethnolichenology and related economic mycology, investigates the relationship between fungi, including lichens, and human culture, that is the historical and current use of fungi and lichens and their sociological impact in human communities (Kreisel 2014). Interest in nature often stems from the desire of people to record and develop their nutritional, medical and cultural foundations. Ethnomycology particularly addresses the triangular relationship between humans, fungal organisms along with abiotic factors of the ecological system in the regions where a given human community lives (Osarenkhoe *et al.* 2014). This knowledge forms the basis for understanding the importance of fungi to past and present civilizations worldwide (Lampman 2010). Medicinal fungi can have significant health benefits and can exhibit a wide range of pharmacological activities (Froese *et al.* 2016; Venturella *et al.* 2021). These activities are due to metabolites produced and secreted by the mycelium, but mainly in the plectenchyma of the fruit body, and their biological effects vary depending on the chemical nature and fungal species (Kreisel 2014). While interactions between humans and fungi go back many millennia and peaked in the foraging era, documented evidence of traditional mycological knowledge is a more recent development. The first scientific papers with a focus on ethnomycological content and 'ethnomycology' in the title appeared in the second half of the last century (Wasson 1971; Singh 1999; Azeem *et al.* 2020). The field of research became a new discipline that developed from ethnobiology (interactions between humans and the environment) and ethnobotany (cultural use of plants) (Kreisel 2014). There has also been overlap with social science disciplines such as anthropology (the study

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of humans) and ethnography (empirical data on human society and culture) (De Kesel & Degreef 2007), and close relationships with other areas of mycology such as economic and applied mycology, which deal with the use of fungi and fungal diseases in humans, animals and plants (crops). Ethnolichenology is concerned with the relationships between lichens and humans (Yang *et al.* 2021). Lichens have been used in traditional foods and medicines for thousands of years and play important roles in ecosystem function and human well-being (Crawford 2015). Lichens and their symbionts fulfil a variety of ecosystem functions (e.g. soil formation, rock decomposition, carbon, and nitrogen fixation) and support the diversity of many organisms, for example by providing habitat, food, shelter, nesting material or camouflage. They also provide numerous direct and indirect ecosystem services, such as secondary lichen metabolites that can be used for medicinal and other purposes, as bioindicators of environmental change, and as a source of inspiration for culture, art and design (Zedda & Rambold 2015).

In the mid-18th century, regular harvests in Europe were severely affected by frosts and droughts, causing famines, and therefore lichens were used as food because of their easy availability, low cost and nutritional value (Llano 1948). Most lichens are non-toxic but there are exceptions, such as *Letharia vulpina* (L.) Hue, *Cetraria pinastri* (Scop.) Gray, *Bryoria fremontii* (Tuck.) Brodo & D. Hawksw. and *B. tortuosa* (G. Merr.) Brodo & Hawksw., due to the vulpinic or pinastric acid they contain (Spribille *et al.* 2016).

In Africa, there is a large number of local (rural) populations, regional cultures, and socio-cultural groups. Associated with these is an extensive regional knowledge about fungi and lichens and their role as food and medicine, as a means of producing food, drinks and medicines, as a source of income, opportunities for small businesses, and sociological impact (myth, culture and spirituality). However, there is a considerable risk that fungi and the traditional knowledge about them of indigenous peoples and local populations will become extinct in the near future, before they are identified and their cultural and economic value documented. Due to the slow progress of ethnomycological research, the majority of oral traditions may remain unrecorded (Osarenkhoe *et al.* 2014). Relevant mycological literature regarding Africa is sparse and limited in scope, with taxonomic inconsistencies (Osarenkhoe *et al.* (2014) for West Africa). In African forests, conservation efforts mainly focus on birds, mammals and vascular plants, while little or no attention is paid to fungi. This is despite the fact that macrofungi not only play an important socio-economic role in traditional Africa cultures (Osarenkhoe *et al.* 2014), but also a central role in ecosystems (Malinowska *et al.* 2004).

Since the mycological knowledge of indigenous tribes and regional populations could serve as a tool for assessing fungal diversity in a country, it would be highly advantageous to document the corresponding socio-cultural knowledge in order to assess the range of species and thus take a first step towards conservation and ecological sustainability.

Despite the great diversity of wild edible mushrooms in Africa, especially in the tropical regions, there are few ethnomycological reports from regional communities in many African countries (Boa 2004). It is noted by Boa (2004) that the countries on the continent with a better coverage of reports of edible fungi use are Morocco, Cameroon, Nigeria, Democratic Republic of the Congo, Kenya, Zambia, Zimbabwe and South Africa. Also, great progress in ethnomycological knowledge has been made in Benin, Togo, Burkina Faso and Gabon (Yorou *et al.* 2014). The poor quality of identification and documentation of edible and medicinal fungal and lichen species has led to inconsistencies in data on their use in folk medicine, nutrition and mythological beliefs. The focus is on subsistence use of wild edible mushrooms and their importance to rural people, although there are still considerable gaps in information (Boa 2004). In addition, documentation of mycological information from traditional communities is essential for advances in related disciplines such as ethnopharmacology (Haro-Luna *et al.* 2022).

Today, there are only a small number of freely accessible databases for ethnomycological data. An example is Edible Fungi of Tropical Africa (EFTA; https://www.efta-online.org/), run by the Meise Botanic Garden, Belgium, with partners from Africa. The database provides an annotated inventory of edible fungi from tropical Africa and a distribution map based on reference specimens and/or georeferenced photographs.

The reliability of the identity of macrofungal and macrolichen species and their use in ethnomycological studies is often low, as species are mainly tentatively identified based on macromorphological traits. Therefore, data collections and databases with structured ethnomycological information have to be established to facilitate the management of fungal names and identification, as well as the exchange of information between researchers, and to streamline workflows for the analysis of different datasets. Openly accessible data collections could describe fungi for diagnostic purposes and provide basic information on the diverse uses of fungi and lichens in the community. Finally, they can give an indication of the current number of taxa or species used by African populations and ethnic groups, as well as the countries from which they have been documented (https://en.wikipedia.org/wiki/List_of_ethnic_groups_of_Africa).

As far as mycology in general is concerned, there are several mycological databases with global coverage for various purposes that are also relevant for identification and nomenclature in an ethnomycological context. These include MycoBank (https://www.mycobank.org/), an online database intended as a service to the scientific community, documenting nomenclature and associated data (e.g. descriptions and illustrations) and Index Fungorum (IF; https://www.indexfungorum.org), a nomenclatural database with Species Fungorum providing taxonomic information on current species concepts, and literature. Index Fungorum and MycoBank both function as official registries of fungal names according to the rules of the International Code of Nomenclature for Algae, Fungi and Plants (Turland *et al.* 2018), and provide services in this regard. GlobalFungi (https://globalfungi.com/) is a global database of fungal occurrences from metabarcoding studies (Větrovský *et al.* 2020) and the FungalTraits Database is for ecology-relevant characteristics (Põlme *et al.* 2020). Another database is LIAS light (Rambold *et al.* 2014), which is used to characterize and identify lichens based on phenotypic and ecological trait data. The database is global and can be accessed at https://liaslight.lias.net/. The GBIF Backbone Taxonomy (https://www.gbif.org/dataset/d7dddbf4-2cf0-4f39-9b2a-bb099caae36c) is a unified, synthetic classification and data collection tool with the aim of capturing and linking all taxon names, for example those provided by the Catalogue of Life, IF and MycoBank nomenclators, to provide a global overview of the names used by GBIF scientific data on the occurrence and observation of fungi and lichens.

In order to obtain a comprehensive overview of the current state of ethnomycological and ethnolichenological surveys in Africa and to promote future collaborative studies, we have embarked on the project described below with the establishment of a new database for the traditional knowledge and use of fungi and lichens in

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Africa as reported in the scientific literature. The requirements for the design of the database are to create an advanced and flexible virtual working environment with a data pipeline based on existing database applications, technical frameworks and components. The African partners should be able to freely define elements, datasets (data records) and add descriptors. All design elements and components should be freely available, the data and technology reusable, and the software open source. The application should work online and offline. Multilingualism is an issue which we plan to address in a later version of the database and app. As a final step, it is planned to run the modules and the working environment on a server network in an African country. Based on these requirements, the EthnoMycAfrica database has been built. In this initial phase, there has been support from the University of Bayreuth and the SNSB IT Center. The latter currently hosts and provides technical support for the network as part of its data science and research activities.

Results and Discussion

The scientific data collection and database application EthnoMycAfrica

The initiative 'Ethnomycological knowledge in Africa' with the database application EthnoMycAfrica was launched in 2021, aiming to create a repository for published ethnomycological and ethnolichenological data, in which the data are available online in a structured and standardized form. The database content is based on literature data derived from relatively recent peer-reviewed publications and books. Primary data, for example from interviews, are not yet included. The thematic focus so far is on macrofungi and lichens as food, but their medicinal, mythological and natural chemical profile is also covered. Information on the traditional use of microfungi (e.g. yeasts), as well as records from ancient African cultures such as in Egypt, can be added later. The data are stored in a relational database, which will allow the team of individual experts from Africa to have complete control over scientific data curation and access to the data collection. So far, the data have been collected by a small number of experts from the different regions of Africa (West, East, North and South Africa). They have the choice of keeping the data private for a period of time, sharing it with other team members in a secure way, or eventually making it available to the public online under a Creative Commons license. In a later version, data entry will be extended bilingually with data entry and display in English and French. As a whole, the database application is ready to support multilingualism and allows advanced account and rights management. The curation history is documented and only accessible to database administrators. So far, a total of 1350 records have been compiled. The papers were located using Google Scholar and searches in the following journals: *CREAM*, *Diversity*, *Economic Botany*, *International Journal for Medicinal Mushrooms*, *Journal of Ethnobiology and Ethnomedicine*, *Journal of Ethnopharmacology*, *Journal of Medicinal Plants Research*, *Lichen Secondary Metabolites*, *Mycosphere*, *The Bryologist*, *The Lichenologist*, and the *Journal of Pharmacognosy and Phytochemistry*. The Index Fungorum database was used to check taxon names for spelling and author citations. The MycoBank taxon name ID (https://www.wikidata.org/wiki/Property:P962) and Index Fungorum ID (https://www.wikidata.org/wiki/Property:P1391) were added as two descriptors (see Wikidata concept of external identifiers as properties).

Records, descriptors and descriptor states in the EthnoMycAfrica database application

A data collection is useful only if it has well-defined conceptual design elements to capture the relevant information as a reusable digital entity, item or entry (see Harjes *et al.* 2020: 12 ff.). With this in mind, the ethnomycology database was built with project-specific descriptors and state/value terminology that corresponds to the internationally agreed terminologies of ethnomycology and economic botany. The database is currently built up by 34 descriptors, 21 of categorical data type (483 categorical states) and 13 free text descriptors (for descriptors see Fig. 1).

The descriptors with their descriptor states are organized in descriptor trees and classified on the basis of various characters and characters states (i.e. traits and trait expressions) (Fig. 2). The list of descriptor states for medicinal usage type is constantly being expanded (Fig. 2).

The descriptors and descriptor states are also available as an HTML questionnaire (see below) that can be used online for data collection (https://www.snsb.info/DiversityDescriptions_UBTMYCethnomycdesc.html) (Fig. 7). Each digital entity/item represents one taxon record in literature (one species). In some cases, several records for one taxon are known from different literature sources and are therefore given in separate entries, distinguished by suffix numbers. The references are recorded in the database. Entries for the secondary metabolites of a taxon from published papers are also included in the database as separate digital entities. The individual items are thus coded by the taxon name cited in the reference document. Consequently, there are several items with the same taxon name, characterized by different descriptors and values (Fig. 3). In this way, each piece of information can be easily traced. For later diagnostic and analytical purposes, these digital entities can be combined by database functions.

Location information is important for many aspects of ethnomycology, from analyzing market flows to tracing cultivation history. Accordingly, the EthnoMycAfrica database provides support for location information. Each record in the literature can be assigned to multiple places of origin, for example the locality where the author of the referenced article collected the sample or, as an informant or researcher, the information, specified by country and region. The specificity of the location information greatly facilitates the analysis of the origin-related data. With detailed data in each of these two categories, it is easy to identify trends from region to country. Figure 4 shows one of the graphical user interfaces for managing the EthnoMycAfrica database content.

DiversityDescriptions (DWB-DD) organizes any kind of description (e.g. descriptions of organisms, taxa or other digital entities or items) by a threefold structure, namely 'item-descriptor-state' or 'item-descriptor-value'. The descriptors (= features, attributes, properties) are not limited to morphological characteristics and functional traits, but can also be physiological, ecological, behavioural survey parameters, and molecular descriptors. In addition, summary data and sample data, such as those obtained in ecological field sampling, are also addressed. The descriptor states or values that make up the item description can be generalized to one of the currently supported data types (categorical states, quantitative values and statistical measures, molecular sequence data and free-form text as fall-back option (Fig. 5); see Harjes *et al.* 2020).

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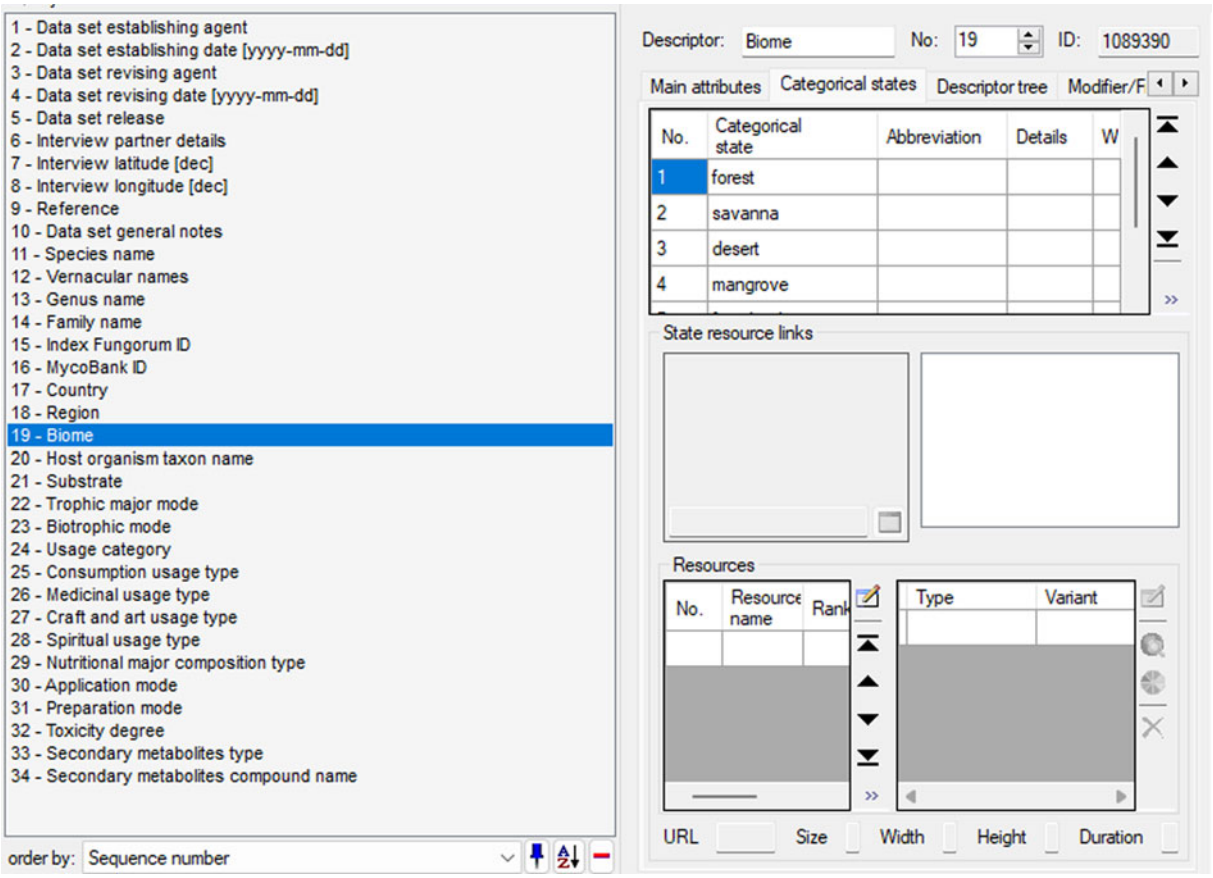

Figure 1. Descriptors and descriptor states of the EthnoMycAfrica database application as seen in the descriptor view of the DiversityDescriptions client. In colour online.

General software architecture

The EthnoMycAfrica database application, with information on traditional use and economically relevant traits of fungi and lichens in Africa, is currently operated at the IT Center of the Bavarian Natural History Collections, Germany, an organization with expertise in biological trait databases. The general design of data entry, scientific data management and data publishing follows the design of the Diversity Workbench (DWB) database framework (see https://diversityworkbench.net/Portal/Diversity_Workbench). DWB data pipelines were implemented for a regional two-country flora project (Novotný *et al.* 2022) and for the global information system LIAS (Rambold *et al.* 2014), among others. In the case of EthnoMycAfrica, the solution involves installing instances of two MS SQL database applications, namely DiversityDescriptions and DiversityProjects, on an MS Windows Server environment. The project's internal scientific and administrative data curation is mainly performed via rich clients. The core system is the hub for importing and exporting content in various standards and formats. The EthnoMycAfrica data pipeline includes four major technical network components that are described as independent segments (Fig. 6): segment 1 is for long-term scientific data curation in DiversityDescriptions, segment 2 for online data generation via HTML questionnaires with schema elements (alternative: offline with stored HTML questionnaire) and segment 3 is organizing the data publication via the DiversityNaviKey architecture. A parallel data publication via structured digital data objects is envisaged as segment 4, which is planned to be carried out in cooperation with the evolving Research Data Commons (RDC) services of the National Research Data Infrastructure (NFDI), Germany (Diepenbroek *et al.* 2021; see also Barker *et al.* (2019) for Australia). Data archiving in the form of Archival Information Packages (AIPs *sensu* Open Archival Information Systems OAIS terminology) is considered as a separate topic to be addressed within each segment. Data archiving is not dealt with here.

For the future, an installation on hardware in Africa is planned. In this context, it is important that segments 1 and 2 can also be operated offline. For segment 3, an online data repository must be maintained in order to operate a server network with web access. Once accessed, the web app can be used offline. Segment 2 and the product of segment 3 use smartphone devices, and segment 1 requires a PC or laptop with MS Windows platform or an emulation of such a platform (see https://diversityworkbench.net/Portal/Technical_documentation_at_a_glance).

Scientific data management system

Ethnomycological knowledge data are entered and maintained in DiversityDescriptions (DWB-DD; see https://diversityworkbench.net/Portal/DiversityDescriptions; Fig. 6, segment 1). DiversityDescriptions is a relational MS SQL Server database with a rich client application. It is a component of the Diversity Workbench (DWB) database framework established to manage research and survey data in study projects. DWB-DD can be

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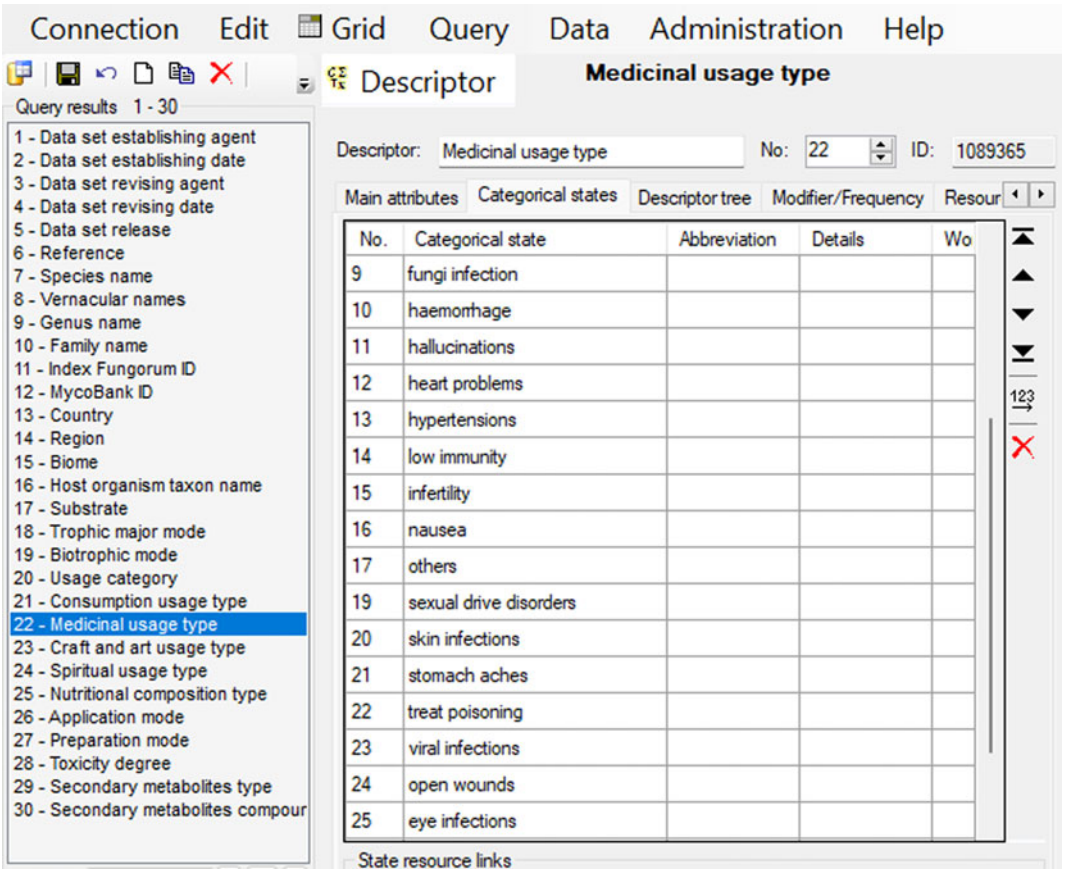

Figure 2. Descriptor states for medicinal usage type of the EthnoMycAfrica database application as seen in the description form view of the DiversityDescriptions client. In colour online.

installed as part of a DWB environment but can also be used as a stand-alone application. DWB-DD allows different editor views, the descriptor view for maintaining descriptors and their states, and a description view for entering and maintaining digital data entities and resource links.

DWB-DD has functions for creating and visualizing simple statistics of items, descriptors and descriptor states, as well as an extended query interface with advanced features. Scientific data management can be organized by establishing study projects and associated study subprojects that use the same descriptor schema or parts thereof. Ethnomycological knowledge data assets need to be managed in a structured way that allows them to be shared with the public in a findable-accessible-interoperable-reusable (= FAIR) manner (for FAIR guiding principles see Wilkinson *et al.* (2016) and Mons *et al.* (2017)). For this reason, a set of commonly agreed administrative, bibliographic, technical and domain-specific data items, so-called metadata, is essential. Within DWB, such data are created, stored and processed in the relational MS SQL Server database application DiversityProjects (DWB-DP; https://diversityworkbench.net/Portal/DiversityProjects). For export, the data are linked to the study projects in DWB-DD. The information models of both DWB applications have been published (see Weiss *et al.* 2018; Hagedorn *et al.* 2023).

Data generation via EthnoMycAfrica HTML questionnaire

DWB-DD has a number of routines and functions, as well as wizards, for organizing the import and export of item descriptor values ('descriptions'). One of the most practical and useful features for the team working on EthnoMycAfrica is the creation and use of the DWB-DD questionnaire for item descriptions (Fig. 6, segment 2). The HTML questionnaire was designed by the EthnoMycAfrica team based on the agreed descriptor scheme. The questionnaire created by the project data administrator is generated as an exported file from DWB-DD and is provided as a web page containing the EthnoMycAfrica descriptor matrix and checkbox options for the categorical descriptors to be selected (see https://www.snsb.info/DiversityDescriptions_UBTMYCethnomycdesc.html) (Fig. 7). The researcher in the office (for data gathering from literature) or in the field (for partner interviews, see general guideline of Alexiades (1996)) enters the data via smartphone or PC/laptop and sends the content data as a TXT document to the EthnoMycAfrica data manager (Fig. 6, segment 2). This is then imported in a one-step process and integrated into the study project. For offline use, the EthnoMycAfrica HTML questionnaire can be downloaded from https://diversityworkbench.net/Portal/DWB_DiversityNaviKey_data_sources.

Data publication via DiversityNaviKey architecture

DiversityNaviKey (DNK) is a web browser-based client developed as a diagnostic tool in the field of biology and related sciences for the identification of organisms, as well as for the interactive selection of other items/entities and objects related to research (Triebel *et al.* 2021; for current software releases see https://divnavikey.snsb.info). The EthnoMycAfrica project-specific structure of

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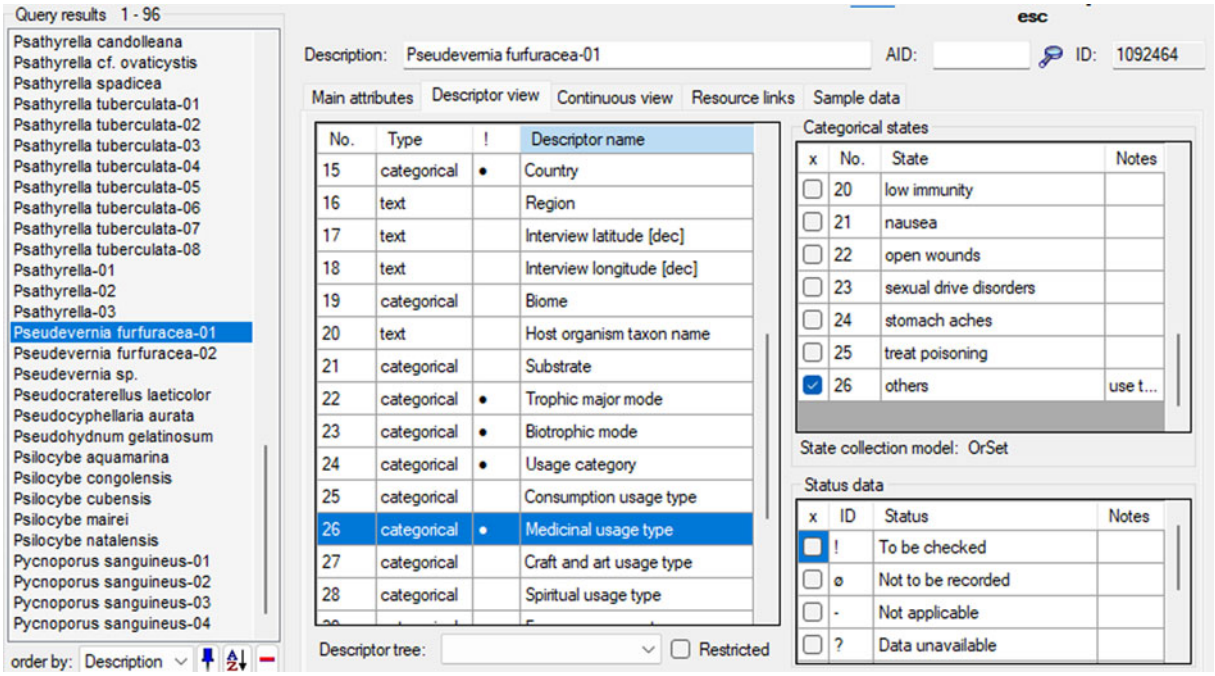

Figure 3. Data items of the EthnoMycAfrica database application as seen in the description view of the DiversityDescriptions client. In colour online.

DNK is based on a set of properties or values of the 34 descriptors. It allows advanced queries of the descriptive data (trait data) to identify groups of objects based on combinations of optionally modified descriptor values that are sequentially selected during the diagnostic process (see Triebel *et al.* (2021) and https://diversityworkbench.net/Portal/DiversityNaviKey). It is somewhat similar to the 'extended query' option implemented in the DiversityDescriptions database client and is adapted for mobile devices.

The DNK is set up as a single-page application and contains the entire presentation logic for dynamically changing the content of a pre-generated HTML page in the browser. The content data are accessed via a web service as JSON packages. DNK is a progressive web application that uses caching mechanisms of browsers, such as Service Worker and IndexedDB. This makes the main tasks available even in offline mode. Apps for capturing or analyzing natural objects (and their use) in the field should be usable (at least under certain circumstances) without

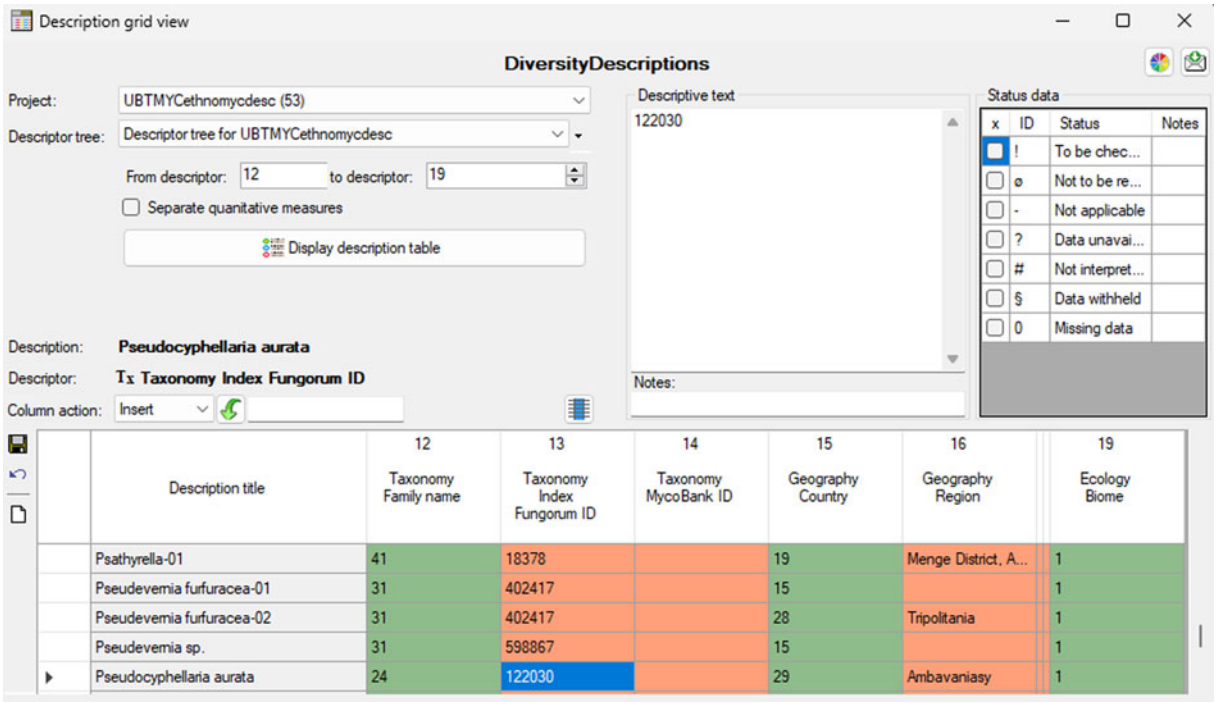

Figure 4. Data items of the EthnoMycAfrica database application as seen in the description grid view of the DiversityDescriptions client. In colour online.

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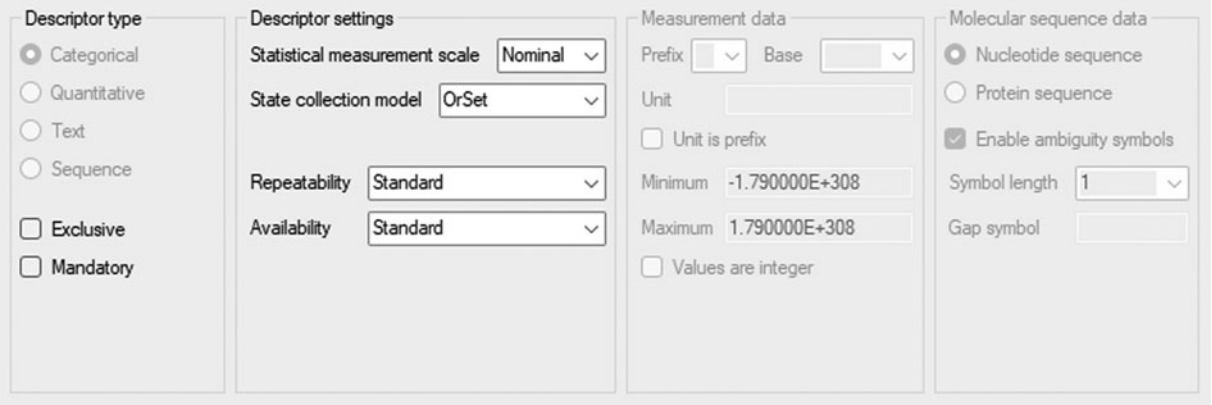

Figure 5. Specifications of the descriptor types in the descriptor view in Diversity Workbench-DiversityDescriptions (DWB-DD).

internet access. This is particularly the case in remote areas of Africa, where the diagnostic process with DNK, as well as data generation via DWB-DD HTML questionnaires, will often be performed offline. Riccamboni *et al.* (2010), Nimis *et al.* (2012) and Nimis & Martellos (2020) have already stated that there should be platform-independent, easy-to-use solutions for mobile devices with an offline mode to meet the user requirements of different scientific and non-scientific communities in this context. The lichen information systems ITALIC, with online identification keys (https://italic.units.it/?procedure=idkeys), and LIAS light with DNK (https://liaslight.lias.net/) are pioneers in this field.

The current set-up of the EthnoMycAfrica working environment uses the DNK architecture with a DB backend of DWB-DD as a productive MS SQL Server database with a PostgreSQL cache database and a RESTful web service API and web application (HTML, JS, CSS) (Triebel *et al.* 2021; Figs 1, 3 & 6 (segment 3)). The new DNK data source EthnoMycAfrica is characterized under https://diversityworkbench.net/Portal/DWB_DiversityNaviKey_data_sources, and is accessible for diagnosis and analysis at https://divnavikey.snsb.info (see Fig. 8).

Data publication via structured digital objects guided by NFDI RDC

Using the DNK as a tool, the structured information in EthnoMycAfrica is freely accessible. The German National Research Infrastructure (NFDI) and the European Open Science Cloud (EOSC) aim to make it accessible and reusable to a broad user community and there are plans to publish the same data content as two digital assets: 1) with domain-specific metadata standardized according to the Ecological Metadata Language EML XML and the EthnoMycAfrica study data in CSV table format, and 2) with domain-specific metadata standardized according to the Ecological Metadata Language (EML) XML and the EthnoMycAfrica study data structured in SDD XML standard, as

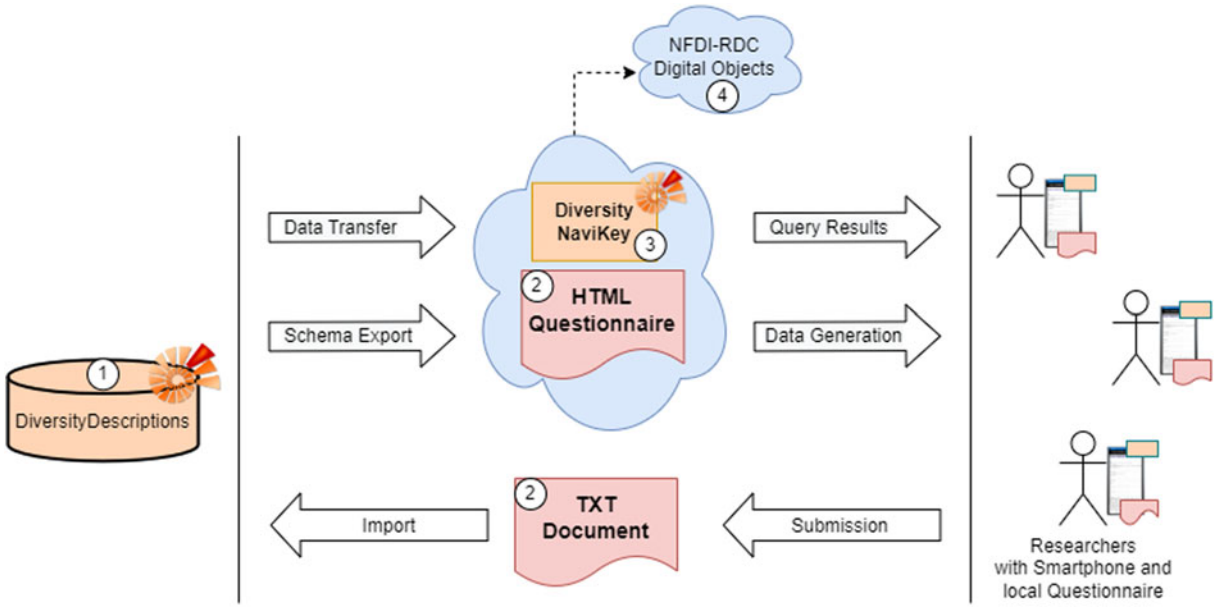

Figure 6. Segments 1–4 of the EthnoMycAfrica data pipeline. Segment 1 is for long-term scientific data curation; segment 2 for online and offline data generation via HTML questionnaires; segment 3 is for organizing the data publication via the DiversityNaviKey architecture; segment 4 is an envisaged parallel data publication via structured digital data objects. NFDI-RDC = Research Data Commons services of the National Research Data Infrastructure, Germany. In colour online.

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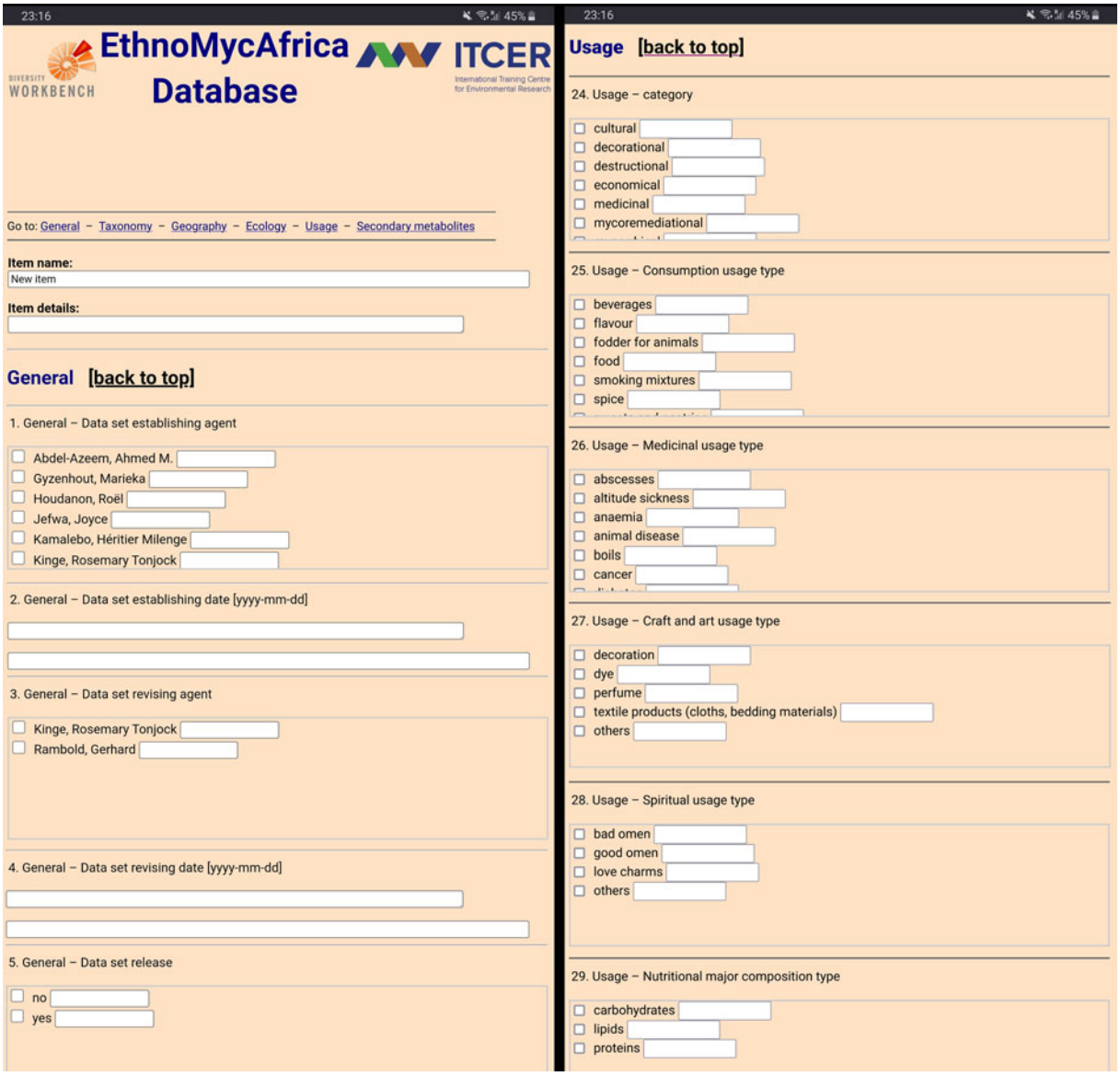

Figure 7. The HTML questionnaire for submitting data to EthnoMycAfrica at http://www.snsb.info/DiversityDescriptions_UBTMYCethnomycdesc.html. In colour online.

described by Harjes *et al.* (2020; Fig. 5 and https://gfbio.biowikifarm.net/wiki/Major_Types_of_Biological_Data). With this kind of publication of DNK processed data (Fig. 6, segment 4), the EthnoMycAfrica data collection will form two Dissemination Information Packages (DIPs *sensu* Open Archival Information Systems (OAIS) terminology) and FAIR digital objects accessible through future NFDI cloud services and tools.

Independently, it is planned to develop a technical concept for integrating DWB-DD-generated HTML questionnaires into the future NFDI-RDC application layer (see Fig. 6).

Database usage

The EthnoMycAfrica database was built over two years and includes 34 descriptors, provenance information, data import and export functions, and a browser-based query interface. The descriptors, mostly categorical, have already been field-tested and populated with information from several hundred records from the literature. Since the descriptors and categorical descriptor states are easily extensible, they can also be adapted and redesigned for future projects that collect additional cultural and biological information. This also applies to the existing questionnaire design, which can be reused for interviews in future projects.

The existing DWB infrastructure has reached a high level of functionality. The software is open source (GNU General Public License 3.0 – GPLv3) and suitable to be reused anywhere without much implementation effort. Therefore, parts of the existing infrastructure can be easily transferred and installed in data hubs in African countries, such as ITCER in Kenya, to achieve data sovereignty. The data are and will be made available under the Creative Commons CC BY 4.0 license. Currently, the data collection comprises 1350 data entities from countries in all parts of Africa. Incoming data are continuously checked for quality using

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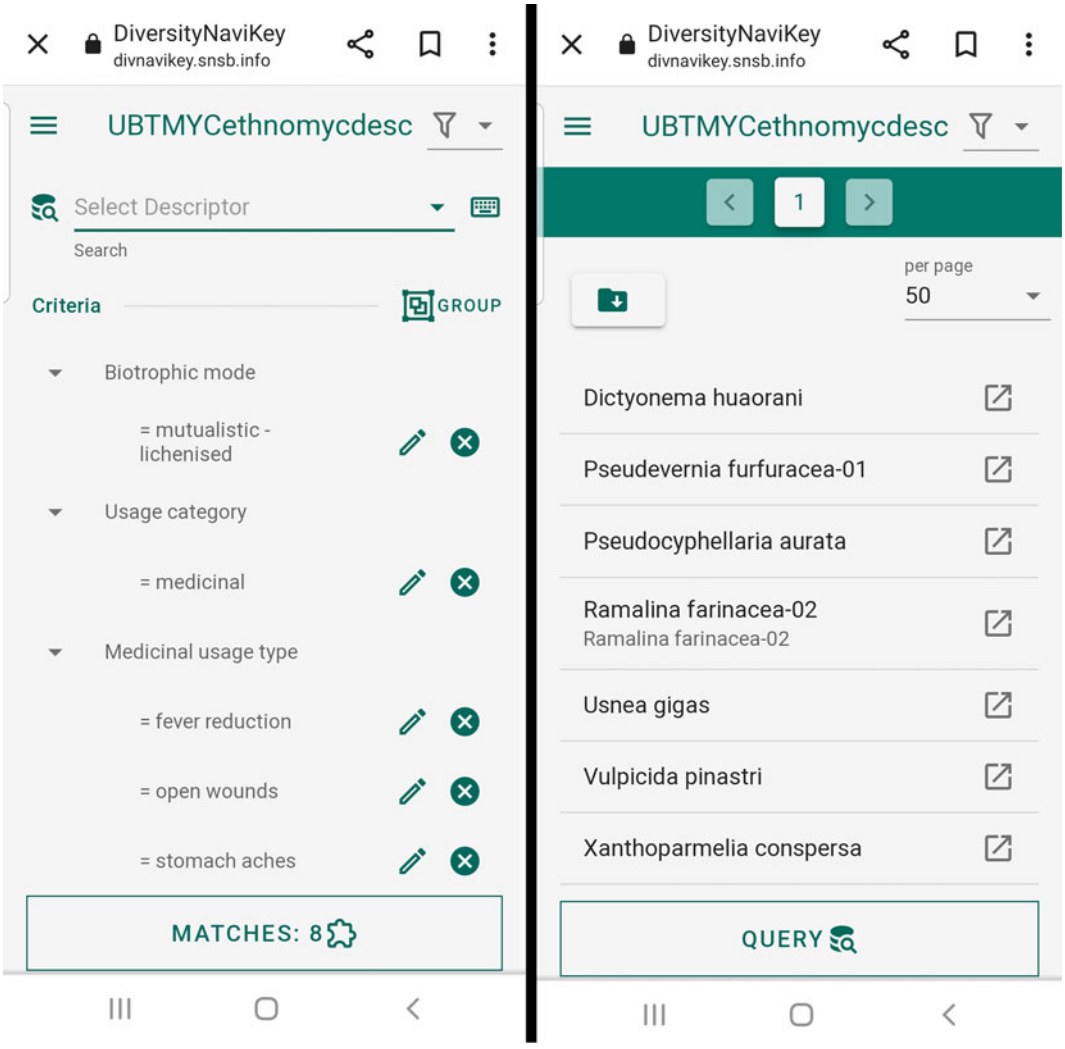

Figure 8. The DiversityNaviKey web app interface with EthnoMycAfrica database content. In colour online.

DWB-DD's internal data validation and maintenance tools. Data can also be used for ethnomycological meta-analyses.

The ongoing and planned activities around the database described here can be divided into the following three phases. For the first phase, a project group with individuals from different areas of Africa compiled evidence of the uses of mushrooms, lichens and microfungi from the available literature. Data were entered directly into subprojects by participants using the DiversityDescriptions client, and records can be transferred to the central project. The entered data will be supplemented in the near future, in particular by references to the French- and German-language literature.

This data pool might be the starting point for activities in the second phase. Interview data will be collected as part of local projects on the ground. This type of local-use project is of particular anthropological interest and could be designed according to the basic concepts published by Alexiades (1996). A specific tool for this approach is the EthnoMycAfrica HTML questionnaire, as described above. This option is of particular interest, since a usable internet connection is required only to send the data by email, in contrast to the DiversityDescriptions client which requires a good internet connection constantly. The content of the database accessed through the DiversityNaviKey web app is updated regularly. In this way, a full cycle from data creation in the field, content import and export, to data retrieval is achieved, and researchers in Africa can work with mobile devices. In addition to overseeing data import, the EthnoMycAfrica project administrator is tasked with performing quality control using the DiversityDescriptions out-of-the-box tools, aligning nomenclature and classification with Index Fungorum, MycoBank and GBIF taxonomy backbones, and organizing export for DNK publication.

The third phase of EthnoMycAfrica activity concerns meta-analyses that can be performed on the entire dataset or parts of it. DiversityDescriptions has functions for visualizing numerical statistics of selected content. Moreover, configurable export options allow appropriate analyses with external statistical programs and GIS applications. Clearly, it will take time to achieve sufficient data density to perform ethnomycological data analyses for large geographical regions of Africa. The cooperation of citizen scientists would be desirable here.

Conclusion and Perspectives

Open-source data technologies and freely accessible information have led to information dissemination among scientists, including

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mycologists and lichenologists, for example through online journals with open access options and social platforms that contribute to a better understanding of the relationships between humans, fungal organisms and their use. However, in many African countries there is a lack of mycological data from local communities, and in many cases mycological data are not well structured and remain difficult to access, sometimes due to insufficient data management. In addition to the facility of storing a large dataset, we refer to the capabilities of the system to generate FAIR++ data in the sense of Harjes *et al.* (2020). To our knowledge, this is the first ethnomycological database for African fungi and lichens with such advanced tools for data generation, storage, visualization and publication. Geographical areas with data gaps can be identified in the database so that future studies can be targeted to areas with insufficient knowledge.

The main purpose of the EthnoMycAfrica database application is to provide information on the use of (macro-)fungi and lichens to mycologists, lichenologists, nutritionists and natural product chemists. Nutritionists can use the information to study the nutritional properties of fungi documented as edible. Natural product chemists can screen potential medicinal macrofungal and lichen candidate species for secondary metabolites with a view to drug development. EthnoMycAfrica beneficiaries include curators of scientific collections, as herbarium staff, rangers, community members, policy makers, anthropologists, researchers, and students who can be helped to understand the uses of these organisms. Sustainability of technical systems and long-term data storage are recognized problems, not just in the life sciences (Attwood *et al.* 2015). The DiversityDescriptions relational database system with its client is open source and free to use. It can be installed locally as a research tool. Thus, the installation and running of the EthnoMycAfrica system in African countries is a realistic option. The content is under the GBIF compliant Creative Commons (CC) license CC BY 4.0. The descriptor schema can be extended and restructured to meet changing needs. The EthnoMycAfrica data pipeline could also be used as a collaborative virtual work environment to which a group of data scientists can contribute their data for their own use, eventually making it publicly available. Incorporated knowledge in this public database can also help to protect against biopiracy (Gupta 2002; Souza & Hawkins 2020). However, the inclusion of new data from interviews of local communities is challenging because the growing number of datasets will include information on occurrences, and also of endangered species, which can then be easily found by collectors and consequently populations might be reduced significantly. When collecting reference material to ensure proper identification, the prior consent of the state agencies is essential in accordance with the Nagoya Protocol on Benefit Sharing Assessment.

We expect the EthnoMycAfrica system to be a source of information and knowledge exchange between users. Although it is currently a suitable solution, there is always room for improvement. Our plans for the future include: 1) reaching out to researchers in the field of ethnomycology to make them aware of the application and how they can contribute with their projects; 2) continuously improving the search and quality control functions of the database; 3) enhancing the DWB-DD interface to make it suitable for African languages; 4) expanding the data collection to include primary data from field studies, along with information on interview partners as individuals (stored in DiversityAgents) and on the timing and duration of use and popularity, if available; 5) establishing a data repository at the ITCER site in Ng'iya, Siaya County, Kenya, where EthnoMycAfrica could be installed to enable the management of ethnomycological data in Africa in the medium term.

Since the EthnoMycAfrica database offers researchers complete control over their own data, supports English and French, the most widely used official languages in African countries, and with its features offers robust functionality and organizational backing, it is a solution useful for anyone conducting research in the field of ethnomycology according to the scheme described here. In future, researchers might undertake ethnomycological studies in these countries, that is collect and classify the relevant knowledge in indigenous communities, assess the use or potential use of these resources in practice, and develop concepts about how indigenous people can benefit from their traditional knowledge. The mobilized data will be made available and will aid conservation of the fungal organisms and, not least, the habitats in which they live.

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Online Resources. https://diversityworkbench.net/Portal/DiversityDescriptions_Information_Models
https://diversityworkbench.net/Portal/DiversityNaviKey
https://diversityworkbench.net/Portal/DWB_DiversityNaviKey_data_sources
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