# Chapter 15
# Census of Yeasts Isolated from Natural Ecosystem and Conserved in Worldwide Collections

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**Abstract** There are many well-known public yeast repositories as well as a large number of smaller, less-known collections worldwide; most of these are with the primary goal to preserve the yeast biodiversity in a specific region and the strains from a range of species that are important environmental strains, food spoilage organisms, or strains that play a role in food preparation and human or animal pathogens. In order to have an overview on how many yeast strains are isolated

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from natural ecosystems and are preserved in collections worldwide, curators of public and private fungal/yeast culture collections were contacted to participate in this survey. Curators of 41 collections from 27 countries supplied data representing a total of 58,095 strains. This includes information on the collection itself, type of environment the strains were isolated from, the countries of origin of the strains, and also the taxonomic information. The ecosystems that are well represented according to the data of preserved strains in the participating collections are plants, insects/invertebrates, aquatic habitats, soil, and extreme cold and extreme warm/dry habitats. The strains have been isolated from a large number of countries worldwide (countries of origin), but it is clear that many parts of the world's ecosystems are not yet well sampled for yeast diversity. A challenge during this survey was to list the genera and species due to the current and constant changes in taxonomic names. The outcome of this survey is discussed in this chapter.

**Keywords** Collections • Environment • Origin • Preserved specimens • Taxonomy • Worldwide

**Contents**



## 15.1 Introduction

There are many well-known public yeast repositories worldwide. Many of these collections are listed at the World Data Centre for Microorganisms (WDCM; http://www.wdcm.org/), which is compiled and validated by the World Federation for Culture Collections (WFCC; http://www.wfcc.info). Thirty-seven of the largest collections are listed in Boundy-Mills et al. (2016), most of these with the primary goal to preserve the yeast biodiversity in a specific region. In addition to these collections, there are also a large number of smaller, less-known collections that also preserve strains from a range of species that are important in different areas such as environmental strains, food spoilage or fermentation, and human or animal pathogens. Many of the public collections have their own searchable online catalog.

The Global Catalogue of Microorganisms (GCM; Wu et al. 2013) is a searchable catalog in which the strain catalogs of more than 100 fungal/yeast/bacterial collections are merged. Different fields can be searched, including the taxonomic name, country of origin, and the isolation source. Unfortunately, GCM is not updated frequently with the current data of the collections.

Natural ecosystems of yeasts vary from aquatic to terrestrial habitats, polluted environments, invertebrates and vertebrates, and their surroundings as well as extreme cold to extreme warm and dry living conditions. Since the 1790s strains have been isolated from natural habitats and described (Kurtzman et al. 2015). Some of those strains are preserved in world-renowned public collections, but it is clear that a large part of the earth's biomes has not yet been sampled for yeasts (Kurtzman et al. 2015), and, unfortunately, many of the thousands of collected strains have not been preserved in culture collections for future generations to use.

In order to have an overview on how many yeast strains, isolated from natural ecosystems, are preserved in collections worldwide, curators of public and private fungal/yeast culture collections were contacted to participate and supply the necessary information on yeast strains isolated from natural habitats in their collections. Curators of 41 collections from 27 countries supplied data representing a total of 58,095 strains. This includes information on the collection itself, type of environment the strains were isolated from (e.g., extreme cold and extreme warm environments, aquatic habitats, plants, soil, forests, grassland, etc.), the countries of origin of the strains, and also the taxonomic information linked to the strains. The outcome of this survey is discussed in this chapter.

## 15.2 Global Effort to Preserve Yeast Strains for Future Generations

Curators of more than 80 collections from different parts of the world were asked to supply data for this survey. While just over half of the curators responded, some of the collections contacted do not preserve yeast strains or only have a limited number of strains, whereas others mainly preserve industrial yeasts or human and animal pathogenic species, which were not of interest for this survey. Other curators did not provide data due to the lack of an appropriate database from which this type of data could be retrieved easily or the lack of manpower to retrieve the data.

Based on survey responses from 41 collections in 27 countries, the information of 58,095 strains obtained from natural ecosystems was made available (Table 15.1). It is important to take into account that one strain can be preserved in two or more collections, as it was logistically not possible to eliminate this factor. From the 41 collections, most collections provided data that could be used in all further analyses (Tables 15.2 and 15.4). Table 15.1 provides an overview of the participating collections with full collection names and what type of data was used in the analyses of the environmental data (Table 15.2), the data from the countries

**Table 15.1** Details of collections that contributed data to this survey

| Region | Country | Full name of collection | Acronym | # of strains | Data included | | |
|---|---|---|---|---|---|---|---|
| | | | | | Table 15.2 | Table 15.3 | Table 15.4 |
| Africa (882) | South Africa | UFS Yeast Culture Collection | UFS | 882 | X | X | X |
| Asia (7588) | China | China General Microbiological Culture Collection Center | CGMCC | 1343 | X | X | |
| | Japan | Japan Collection of Microorganisms | JCM | 1572 | X | X | X |
| | Thailand | BIOTEC Culture Collection | BCC | 3951 | X | X | X |
| | Thailand | Thailand Bioresource Research Center | TBRC | 516 | X | X | X |
| | Thailand | TISTR Culture Collection, Bangkok MIRCEN | TISTR | 206 | X | X | X |
| Australia and New Zealand (326) | Australia | Plant Pathology Herbarium | BRIP | 99 | X | X | |
| | New Zealand | International Collection of Microorganisms from Plants | ICMP | 227 | X | X | X |
| Europe (15,055) | Belgium | MUCL Environmental and Applied Mycology | BCCM/MUCL | 1077 | X | X | |
| | France | Centre International de Ressources Microbiennes-Levures | CIRM | 354 | X | X | |
| | Germany | Leibniz-Institut DSMZ-Deutsche Sammlung von Mikroorganismen und Zellkulturen GmbH | DSMZ | 278 | X | X | |
| | Greece | University of Athens/Hellenic Collection of Pathogenic Fungi | UOA/HCPF | 92 | X | X | |
| | Hungary | National Collection of Agricultural and Industrial Microorganisms | NCAIM | 336 | X | X | X |
| | Italy | Industrial Yeasts Collection DBVPG | DBVPG | 3010 | X | X | X |
| | Netherlands | CBS Collection, Westerdijk Fungal Biodiversity Institute | CBS | 4074 | X | X | X |
| | Portugal | Portuguese Yeast Culture Collection | PYCC | 2085 | X | X | |
| | Slovakia | Culture Collection of Yeasts | CCY | 265 | X | X | X |
| | Slovenia | Microbial Culture Collection Ex | EX | 3003 | X | X | X |
| | Slovenia | ZIM Collection of Industrial Microorganisms | ZIM | 139 | X | X | X |
| | Spain | Coleccion Espanola de Cultivos Tipo | CECT | 141 | X | X | |
| | Switzerland | Culture Collection of Switzerland | CCOS | 47 | X | X | |
| | United Kingdom | National Collection of Yeast Cultures | NCYC | 154 | X | X | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| North America (17,809) | Canada | Department of Plant Sciences, University of Western Ontario | UWOPS | 4473 | X | X | X |
| | USA | USDA Agricultural Research Service Culture Collection | NRRL | 7463 | X | X | X |
| | USA | Culture Collection of Meredith Blackwell | Blackwell | 2040 | X | X | X |
| | USA | Phaff Yeast Culture Collection | UCDFST | 3833 | X | X | X |
| South America (11,533) | Argentina | Culture Collection of Diego Libkind | Libkind | 960 | | X | X |
| | Brazil | Coleção de Culturas Microbianas Carlos Rosa | CCR | 2268 | X | X | X |
| | Brazil | Culture Collection of Microorganisms and Cells | UFMG | 4492 | X | X | X |
| | Brazil | Laboratory of Molecular Diversity of Federal University of Alagoas | UFAL | 257 | X | X | X |
| | Brazil | UNESP Microbial Resources Center | CRM-UNESP | 374 | X | X | X |
| | Brazil | Universidade Federal de Pernambuco | URM | 55 | X | X | X |
| | Brazil | Universidade Federal do Rio Grande do Sul Yeast Culture Collection | UFRGS | 103 | X | X | X |
| | Colombia | Yeast Culture Collection of Universidad del Valle | UNIVALLE | 15 | X | X | X |
| | Ecuador | Colección de Levaduras Quito Católica | CLQCA | 3009 | X | X | X |
| Former USSR (4702) | Belarus | Belarus Collection of Microorganisms | BIM | 240 | X | X | |
| | Russia | Yeast collection of Lomonosov Moscow State University | KBP | 1374 | X | X | |
| | Russia | Collection of the Institute of Viticulture and Oenology | Magarach | 886 | X | X | |
| | Russia | All-Russian Collection of Microorganisms | VKM | 1089 | X | X | |
| | Russia | Russian National Collection of Industrial Microorganisms | VKPM | 482 | X | X | |
| | Ukraine | Ukrainian Collection of Microorganisms | UCM | 831 | X | X | |

The total number of strains per region is indicated with the region name

of origin (Table 15.3), and the taxonomic information on the strains from the different environments (Table 15.4).

The highest numbers of strains obtained from natural ecosystems are preserved in collections in North America (17,809), Europe (15,055), and South America (11,533). The collections that have preserved large numbers of natural isolates are NRRL (7463), UFMG (4492), UWOPS (4473), CBS (4074), BCC (3951), UCDFST (3833), DBVPG (3010), CLQCA (3009), and EX (3003). The majority of the curators provided a short description of their collections, including some history, interesting facts, and core activities.

### *15.2.1 African Collection*

Most strains in the UFS collection (South Africa) were isolated by J.P. van der Walt and co-workers during 1953–1987. The collection contains almost 3000 strains of diverse taxonomic affinities, of which many were collected from fynbos (shrubland) ecosystems. It constitutes the largest collection of its kind in Africa. In 1996, the UNESCO awarded a MIRCEN status to the department of the collection to develop and support microbiology and microbial biotechnology in Southern African countries, thereby making industrial biotechnology the primary focus of UFS.

### *15.2.2 Asian Collections*

CGMCC (China) was founded in 1979 as the central collection in the network of various collections in China. The main focus is to preserve, supply, and maintain living microbial resources and contribute to scientific communities. The collection maintains approximately 40,000 strains (as of late 2013), of archaea, bacteria, and fungi including yeasts. One of the aims is to improve and expand the collection continuously by exploiting new microbial resources from various natural environments.

JCM (Japan) is the biggest culture collection in Japan. It was established in 1981. Since 2004 this collection has participated in the RIKEN BioResource Center (BRC). Its mission is to contribute to scientific communities by maintaining and serving high-quality bacterial, archaeal, and fungal resources for various research fields, particularly in health and environmental sciences. It maintains more than 26,000 microbial strains of which 16,000 are publically available that include 2600 yeast strains.

BCC (Thailand) was founded in 1996. Its primary objective is to collect and maintain microorganisms and their relevant data for in-house research at the National Center for Genetic Engineering and Biotechnology (BIOTEC). Microorganisms are tested to find valuable products such as secondary metabolites, enzymes, and bioactive short peptides. The collection maintains more than

80,000 strains of which approximately 75% are taxonomically and ecologically diverse filamentous fungi/yeasts. The largest group is those isolated from insects.

TBRC (Thailand) was established in 2015 and operates under the jurisdiction of BIOTEC, the National Science and Technology Development Agency (NSTDA), and under the Ministry of Science and Technology (MOST). It preserves, provides, and facilitates the coordination of exchange of biological information and resources and develops mechanisms enabled by information technologies. The TBRC Network represents the commitment to generate economic value and enhance the competitiveness to the ASEAN Economic Community (AEC) from its rich biological resources. Approximately 2500 strains of bacteria, yeasts, and fungi are preserved in this collection.

TISTR (Thailand) was created with UNESCO/UNEP's support since 1976 to serve as an MRC (Microbial Resource Centre) for Southeast Asia with the aim of establishing a holding center for agriculturally and industrially useful microbial strains. It has been devoted to collection, preservation, and distribution of microorganisms and consists of more than 5000 strains of bacteria, yeasts, fungi, and microalgae, covering a wide range of known or potential applications for biotechnology development, agriculture, environment, and industry.

### *15.2.3 European Collections*

DSMZ (Germany) originated in 1968 when the microbial service collection was launched at the Institute for Microbiology in Göttingen. The collection, under the name "DSM—Deutsche Sammlung von Mikroorganismen," became independent in 1976. In 1987 the collections of actinomycetes and Gram-positive bacteria were transferred to DSM from Darmstadt and Munich, respectively. The collection became an independent institution in the end of 1988. It is now one of the 89 institutes of the Leibniz Association. The collection holds presently 700 yeast strains (Boundy-Mills et al. 2016), which were accumulated from German universities and institutions. DSMZ also maintains patent and type strains.

The UOA/HCPF (Greece) was founded in 1995. It is the only registered national culture collection for yeast/fungal human and animal pathogens, their genetic material, and metabolites. The collection currently holds 3225 strains of yeasts and 1765 strains of filamentous fungi. Services include the distribution of strains; isolation and identification of strains from clinical specimens and from substrates related to public health, safety and welfare, consulting service, and screening; and characterization of fungal strains for useful properties.

The predecessor of NCAIM (Hungary), the Hungarian Microbiological Gene Bank (HMGB), was established in 1974. In 1985 NCAIM became a centralized culture collection. The mission of this collection includes (among others) participating in ex situ conservation of microorganisms and supplying microorganisms to interested parties. The main research activity of NCAIM is directed to the

investigation of biodiversity and systematics of yeasts. Currently it maintains 1760 yeast, 1390 bacteria, and 330 filamentous fungal strains.

In 1912 DBVPG (Italy), or at that time "Collezione dei Lieviti Vinari dell'Istituto di Microbiologia Agraria e Tecnica" (acronym IMAT), was founded. The main objectives are the acquisition, classification, preservation, and distribution of strains. Research focuses on taxonomy, biodiversity, and biotechnology of yeasts. It maintains about 6000 yeast and yeastlike strains associated with the alcohol fermentation industry and strains isolated from different environmental and food-associated habitats including many psychrophilic and psychrotolerant strains.

CBS (the Netherlands) is a collection of the Westerdijk Fungal Biodiversity Institute, formerly known as the CBS-KNAW Fungal Biodiversity Centre, that maintains a collection of filamentous fungi, yeasts, and bacteria and is the biggest collection of its kind. The institute's principal focus is on the taxonomy and evolution of fungi as well as on functional aspects of fungal biology and ecology. The collection maintains approx. 100,000 strains, of which more than 10,000 are yeasts, representing a large percentage of the species cultured to date. It also maintains patent and type strains. In diversity of species, it is unchallenged as a reference center for mycological research. CBS has several active research groups and gives advice on mycological problems of a scientific, health-related, or industrial nature.

PYCC (Portugal) was founded 1952; it is a service and research collection that provides support to R&D activities in Portugal and abroad. The collection serves as a repository of yeast biodiversity and genetic resources, with emphasis on Mediterranean foods, beverages, and natural habitat. It holds approximately 4000 yeast strains that represent most of the known diversity of this group of microorganisms. About 1500 strains are unique in this collection and were obtained in ecological studies carried out by researchers of the laboratories that housed the collection.

The CCY (Slovakia) is the largest general yeast collection in Slovakia. It holds 3600 strains of yeasts and yeastlike organisms including biotechnologically important strains, strains isolated from different contaminated sources, from various ecological niches, strains with specific characteristics, mutant strains, and type and patent strains. The collection is expanding with industrially and scientifically interesting strains. The biotechnology, food, and pharmaceutical industries have had a long and profitable association with the yeasts in the collection.

EX (Slovenia) was established in 1998. It is one of the few collections in the world that are specialized in the isolation and preservation of extremophilic microorganisms, including hypersaline environments such as different salterns. Extremophilic fungi represent the majority of strains, although extremophilic bacteria and archaea are also preserved by EX.

The ZIM (Slovenia) was systematically organized in 1991, although activities started in 1947. It maintains 2470 yeast strains, 259 filamentous and wood-decay fungi, and 932 bacteria, all isolated mostly from various ecological niches in Slovenia. Objectives are preservation of strains as genetic potential for biotechnological and food applications, taxonomic studies, and application of identification

techniques for the detection of prevalence, abundance, and origin of individual groups of microorganisms.

CECT (Spain) is the only public microbial Biological Resource Centre (mBRC) in Spain. It was started by J. R. Villanueva as a research collection in 1960. It serves as a repository and provider of bacteria, archaea, yeast, and filamentous fungi and has grown steadily and currently registers over 8490 strains. It aspires to act as an interface connecting Spain with worldwide efforts in this field and works together with other collections to help boost European competitiveness in biotechnology.

The CCOS (Switzerland) is the Swiss national public culture collection for bacteria, yeasts and fungi, cell lines, and plasmids. It contains over 1000 strains, and its mission is to preserve the microbial diversity and to enhance the value and quality of biological material for science and industry. CCOS was initiated in a Swiss CTI project and was founded as a corporation in 2010.

NCYC (United Kingdom) originated as a collection of British brewing yeasts with the aim to safeguard brewery microbial sources. It became a National Collection in 1948 and continued to broaden as numerous yeast strains associated with food production and food spoilage and from the natural environment became of great interest. The collection now contains more than 4000 strains including brewing yeasts, yeasts associated with food spoilage, yeasts of medical and industrial importance, as well as strains from natural environments.

### *15.2.4 New Zealand Collection*

ICMP had its origin in 1952 as the personal collection of plant pathogenic bacteria and rhizobia of D. W. Dye. In 1992, the collection was transferred to Landcare Research, one of eight government-owned "Crown Research Institutes." The collection focuses on globally sourced plant pathogens and fungi of New Zealand and the South Pacific. The over 20,000 strains are roughly evenly split between bacteria and fungi/yeasts, including 900 type and pathotype strains.

### *15.2.5 North American Collections*

UCDFST (USA) is the fourth largest collection of its kind in the world (Boundy-Mills et al. 2016), containing over 7500 strains. This collection contains 3695 strains of yeasts belonging to more than 550 species which were originally isolated from natural ecosystems including plants, insects, animals, air, soil, and water. This collection was compiled primarily by eminent yeast ecologist and taxonomist H. J. Phaff (1913–2001). The collection contains over 700 strains of *Saccharomyces cerevisiae* from environmental sources and over 400 strains of the cactus-associated yeast *Pichia cactophila*.

NRRL (USA) opened in 1940 as the Northern Regional Research Laboratory. The goal of the laboratory was to utilize agricultural commodities. One component was to develop fermentation processes for crop utilization, and because of this, the culture collection was established. The collection specializes in yeasts, filamentous fungi, bacteria, and actinomycetes. Current work includes genome sequencing of yeasts, filamentous fungi, and bacteria, especially those of agricultural and biotechnological importance.

The most important collection of yeasts isolated from insects is the Blackwell collection (USA). This collection is the outcome of the "beetle belly yeast project" under the supervision of S.-O. Suh during the years 1996–2007. Methods for dissecting the beetles and isolating the yeasts from their gut were developed, and during the first years, 650 strains of 290 different genotypes were isolated from insects or their habitats. Among these were 200 undescribed taxa. In 2014, approximately 2000 strains were sent to CBS for preservation.

A. Lachance began the UWOPS collection (Canada) in 1979 with *Kluyveromyces* type strains received from the Phaff collection and strains isolated in his yeast course. Additions to the collection were from local cherry black knots and oak exudates as well as strains from different collection trips to the Caribbean, Arizona and Florida (1985), Hawaii (1987), and Mexico (1991, 1994). An enormous collection from floricolous insects of Eastern Australia was added in 1995. In the late 1990s, yeasts from the South Pacific islands, Costa Rica, and Hawaii were added.

### *15.2.6 South American Collections*

The Libkind (Argentina) yeast culture collection holds more than 3500 yeast strains from Patagonian natural environments, with special focus on extremophilic and polyextremophilic yeasts. The objectives of the collection are to preserve natural microbiota of Andean Patagonia pristine environments and the bioprospecting of biotechnological relevant traits. Although not publically available, this collection is still a very important collection of interesting yeasts isolated from natural environments in Argentina.

The CCR collection (Brazil) is a work collection linked to the Laboratório de Microbiologia Ambiental e Biotecnologia and Laboratório de Microbiologia Aplicada of the Universidade Federal do Tocantins. It was created in 2010 to provide a center for the deposit of strains from substrates in the wide area of Brazilian northern Cerrado and Amazonia. It has around 5000 yeast strains and 3000 filamentous fungal strains and also about 900 bacterial strains.

The CRM-UNESP collection (Brazil) started in 2013 to preserve microbial genetic resources isolated by researchers from UNESP. The majority of the microorganisms are filamentous fungi and yeasts from diverse sources such as social insects (mostly attine ants), terrestrial and marine Antarctic samples, and marine invertebrates from the Brazilian coast.

UFAL (Brazil) was founded in 2013. The first strains were obtained from water tanks of bromeliads of the Atlantic Rain Forest in Northeast Brazil. Other substrates include flowers, fruits, leaves of plants of the Atlantic Rain Forest and Caatinga (a type of dry scrubland vegetation), and marine invertebrates. The collection contains approximately 550 strains. The main objectives are to isolate the yeast communities of different Brazilian biomes, to describe possible new species, and to bioprospect these for biotechnological applications.

UFMG (Brazil) started in 2007 to preserve the yeasts isolated from natural habitats in Brazil. It has approximately 45,000 yeast strains, including the research collection, that make it the largest collection in Brazil and is the most representative collection of the existing tropical Brazilian biodiversity. The main goals are to know the yeast biodiversity in tropical habitats and Antarctica and to describe new yeast species together with their biotechnological exploitation. A total of 5985 yeast strains, with identities confirmed by sequencing, have been deposited in this collection.

UFRGS (Brazil) was founded in 2003, and its core purpose is to preserve yeast strains isolated from South Brazilian substrates. It has 103 strains in total, mostly isolated from the phylloplane, flowers and fruits of bromeliads, macrophytes associated with marshlands, and fermented products such as wine and cheese. Besides identification, all strains are tested for biotechnological potential (enzyme production, ester production, and oleaginous nature).

UNIVALLE (Colombia) began its activities in 2008, and its core purpose is to conserve yeast strains from different Colombian substrates, such as lakes, fruits, and flowers from plants and fermented beverages. Besides identification of novel strains and species, all strains were tested for biotechnological potential (enzyme production and fermentation).

Since 2006, CLQCA (Ecuador) is the repository of wild yeasts isolated on substrates located all over the 24 provinces in Ecuador, including the Galápagos Islands. It holds more than 3000 strains. It is not commercial but shares strains with other collections on the basis of research agreements. The curator, J. Carvajal Barriga, was the founder of the collection, and his main interests include biorefineries, microbial archaeology, and the production of beer and other fermented beverages.

### *15.2.7 Collections of the Former USSR*

BIM (Belarus) is the central microbial service collection in Belarus. It holds type and reference material as well as strains potentially useful for industrial

applications. The collection operates as a department of the Institute of Microbiology of the National Academy of Sciences of Belarus. The department was founded in 1975. The yeast collection holds more than 240 strains from diverse taxonomic groups, most of which are species of industrial interest.

KBP (Russia) was founded in the 1950s, and the majority of yeast strains were isolated from soil and other natural habitats by I. P. Babjeva, I. S. Reshetova, I. Y. Chernov, and co-workers. The collection is operated as the research collection that preserves the biodiversity of yeasts isolated during research projects of the Department of Soil Biology on the territory of mainly the USSR. KBP joined the project called "Noah's Ark" to consolidate available university research collections into a single depository.

Magarach (Russia) is focusing on yeasts for wine fermentation and was founded in 1893. Since 1907, yeast strains as well as the spoilage microorganisms were preserved and propagated in the laboratory for teaching and industrial applications in the Magarach wine school. This collection focused on industrial wine yeasts and spoilage agents. Yeast strains were mainly collected in the territory of the USSR.

The central service collection of the Soviet Union, VKM (Russia), was founded in 1958 (Golubev 2008). In 1964 they consolidated the material from the 30 culture collections then present in the former USSR. The yeast collection started from the strains obtained by V. I. Kudryavtsev in the 1930s across the USSR. The VKM was expanded mainly with the strains recovered by microbiologists from the republics of the Soviet Union and via exchange of the material with other collections from various countries. Presently, the VKM is the largest microbial collection in Russia.

VKPM (Russia) is a state service collection that specializes in deposition, identification, certification, storing, and distribution of strains, which are used for research purposes and serve the needs of biotechnological industry. The collection was founded in 1969 as a state repository of industrial microorganisms. Since 1991, the collection is named Russian National (also as All-Russian) Collection of Industrial Microorganisms. The collection received the BRC status in 2014.

UCM (Ukraine) started in 1929 as the collection of reference and research strains of the Institute of Microbiology and Epidemiology of the Academy of Sciences of the Ukrainian SSR (originally, All-Ukrainian Academy of Sciences). At present, the collection holds bacterial, mollicute, fungal, and yeast strains isolated from various sources. The Institute of Microbiology and Virology, which hosts the UCM, established the yeast collection, which mainly includes strains isolated in Ukraine.

## 15.3 Range of Natural Habitats of Preserved Strains

Table 15.2 lists the natural ecosystems from which 57,135 yeast strains were isolated. The ecosystems that are affiliated with yeasts, according to the data of preserved strains in the participating collections, are plants (31.7%), insects/invertebrates (20.1%), aquatic habitats (12.6%), and soil (9.5%). Extreme warm/dry

**Table 15.2** Overview of the representation of different ecological niches in the contributing collections

| Primary category | % of strains in category[a] | Subcategory | % of strains in subcategory[b] |
|---|---|---|---|
| [c]Vertebrates | 2.2 | Animals (no additional information) | 89.3 |
| | | Bovine/equine/swine/poultry | 4.1 |
| | | Reptiles/turtles | 7.0 |
| [c]Atmosphere | 1.0 | Outside/inside buildings | 100.0 |
| Aquatic habitats | 12.6 | Water (no additional information) | 35.9 |
| | | Water from lakes, rivers, springs, and ponds | 21.0 |
| | | Water and soil from sea | 39.3 |
| | | Soil from rivers, swamps, and mangroves | 2.8 |
| | | Soil from hot springs | 1.2 |
| Extreme cold habitats | 5.4 | Antarctic regions (no additional information) | 13.6 |
| | | (Melted) ice, sediment, snow, or water | 22.0 |
| | | Soil, mountains, rocks, or glaciers | 61.7 |
| | | Seawater (Arctic) | 2.5 |
| Extreme warm and dry habitats | 6.1 | Desert plants, mostly cacti | 87.7 |
| | | Desert soil or insects | 11.8 |
| | | Soil from volcanos | 0.1 |
| Forests and woodlands | 3.2 | Forests (no additional information) | 52.1 |
| | | Fruit or flowers from plants | 22.4 |
| | | Forests near lakes, rivers or sea | 8.3 |
| | | Soil from (rain) forests or woodlands | 17.4 |
| Fungi and lichens | 2.0 | Mushrooms/fungi/lichens | 100 |
| Insects and invertebrates | 20.1 | Insects (no additional information) | 24.7 |
| | | Ants or termites | 3.1 |
| | | Bees (including honey) | 15.0 |
| | | Beetles | 36.4 |
| | | Flies, moths, caterpillars | 2.0 |
| | | Insects from plants in forests | 16.5 |
| | | Insects living in the vicinity of water (lakes, rivers, ponds, meadows, and sea) | 0.3 |
| | | Insects living in mountains | 0.1 |
| | | Marine invertebrates | 1.6 |
| | | Arthropods and isopods in vicinity of water | 0.1 |
| Plants | 31.7 | Plants (no additional information) | 48.2 |
| | | Flowers (including wild and grass) | 9.4 |
| | | Leaves or stems | 2.7 |
| | | Fruit (mostly wild) | 10.4 |
| | | Plant or tree exudates | 1.8 |
| | | Rotting and decaying plants or wood | 16.0 |
| | | Trees (including frass) | 4.4 |
| | | Plant phytotelma | 4.7 |
| | | Agricultural plants | 2.5 |

(continued)

**Table 15.2** (continued)

| Primary category | % of strains in category[a] | Subcategory | % of strains in subcategory[b] |
|---|---|---|---|
| Soil | 9.5 | Soil (no additional information) | 71.7 |
| | | Soil from hard ground such as caves, caverns, mountains, and rocks | 15.1 |
| | | Soil from grasslands or meadows | 2.1 |
| | | Sandy soil | 0.8 |
| | | Agricultural soil | 0.8 |
| | | Soil surrounding fynbos | 0.7 |
| | | Acid boreal (podzolic) soil | 0.3 |
| | | Uncultured soil | 8.5 |
| | | Soil (no additional information) | 71.7 |
| [c]Traditional beverages | 6.2 | Fermented | 100.0 |

[a]% of the 57,135 strains for which data was available for this table
[b]% the specific subcategory makes out from the primary category
[c]Categories not included in data of all collections

(6.1%) and extreme cold (5.4%) habitats were also included in the list. There are many important subcategories within the main ecological groups that are also well associated with yeasts: rotting and decaying plants or wood (16.0%); beetles (36.4%); bees (15.0%); soil in extreme cold habitats including glaciers, rocks, and mountains (61.7%); water and soil from the sea (39.3%); freshwater such as lakes and rivers (21%); and plants from extreme warm habitats, mostly cacti (87.7%). The percentages for the specific subcategories are made out from the primary category. Many of the strains from the EX collection (approx. 1500) were obtained from extreme cold environments and make up almost half of the strains from this environmental niche listed in Table 15.2. Almost 20% of the insect-related strains are from the Blackwell collection, and approximately half of the 3833 strains from the UCDFST collection were obtained from extreme warm and dry environments.

## 15.4 Countries of Origin

It is clear that many parts of the world's ecosystems are not yet well sampled for yeast diversity (Kurtzman et al. 2015; data from online collection catalog searches). Table 15.3 gives an overview of the countries of origin of 54,419 of the strains preserved in the participating collections. The remaining strains are from unknown origin. Strains from this survey were isolated from more than 200 countries or regions. Most strains were collected in the USA and Brazil (>7000 strains each), followed by Ecuador, Slovenia, and Thailand with 1000–2000 strains each and with

**Table 15.3** Overview of the number of strains per country (left side of table) and number of strains per region (right side of table) present in the contributing collections

| # of strains/ country listed | Countries | Regions or states | # of strains/ region listed |
|---|---|---|---|
| <30 | Algeria; Azerbaijan; Bhutan; Bolivia ; Botswana; Brunei; Burkina Faso; Burma; Cambodia; Cameroon; Colombia; Congo; Dominica; Egypt; Estonia; Fiji; Guatemala; Guyana; Honduras; Ireland; Ivory coast; Kazakhstan; Kenya; Korea; Laos; Latvia; Liberia; Luxemburg; Malta; Mauritius; Monaco; Mongolia; Morocco; Mozambique; Nepal; Netherlands Antilles; Nigeria; Pakistan; Peru; Poland; Qatar; Romania; Saudi Arabia; Singapore; Somalia; South Africa; Marion island; South Korea; Suriname; Swaziland; Tajikistan; Trinidad and Tobago; Tunisia; Uganda; United Arab Emirates; Uruguay; Vanuatu; West Indies; Yugoslavia; Zimbabwe | | |
| 30–50 | Antigua; Greenland; Indochina; Kyrgyzstan; Madagascar; Serbia; Sri Lanka; Turkey; Uzbekistan | | |
| | Czech Republic | Bohemia | <30 |
| | Georgia | Abkhazia | <30 |
| | Scotland | Shetland Islands | <30 |
| | Tanzania | Serengeti | <30 |
| 50–100 | Bulgaria; Ethiopia; Haiti; India; Lesotho; Moldova; Montenegro; Turkmenistan; Venezuela; Belarus | | |
| 100–150 | Armenia; Austria; Burundi; Croatia; Denmark; Dominican Republic; Greece; Iceland; Switzerland; Ukraine | | |
| | Indonesia | Java | <30 |
| 150–200 | Belgium; Belize; Iran; Israel; Jamaica; Malaysia; Taiwan | | |
| 200–300 | Chile; Finland | | |
| | France | Reunion | <30 |
| 300–400 | Cuba; French Guiana; Hungary; Papua New Guinea; Slovakia; Sweden | | |
| | France | Reunion | <30 |

(continued)

**Table 15.3** (continued)

| # of strains/ country listed | Countries | Regions or states | # of strains/ region listed |
|---|---|---|---|
| 400–500 | Bahamas; Costa Rica; Vietnam | | |
| | New Zealand | Cook Islands | <30 |
| | United Kingdom (UK) | Falkland islands; Virgin Islands, Wales | <30 |
| | | British Indian Ocean | 50–100 |
| | | Cayman Islands | 100–150 |
| 500–1000 | Antarctica; Australia; Germany; Mexico; Norway; Spain; Ukraine | | |
| | Netherlands | Saint Martin | <30 |
| | Portugal | Madeira Islands | <30 |
| 1000–2000 | Argentina; Canada; China; Japan; Panama | | |
| | Italy | Sardinia | <30 |
| | Russia | Crimea | 100–150 |
| | South Africa | Marion Island | <30 |
| 2000–3000 | Ecuador; Slovenia; Thailand | | |
| >7000 | Brazil | | |
| | United States of America (USA) | Wisconsin (WI); Illinois (IL); Maine (ME); Maryland (MD); Minnesota (MN); New Mexico (NM); New York (NY); Pennsylvania (PA); South Carolina (SC); Texas (TX); Utah (UT); Virgin Islands; Virginia (VA); Wyoming (WY) | <30 |
| | | Georgia (GA); Puerto Rico | 30–50 |
| | | California (CA); Navassa Island; North Carolina (NC); Tennessee (TN) | 50–100 |
| | | Florida (FL) | 150–200 |
| | | Arizona (AZ) | 400–500 |
| | | Louisiana (LA) | 500–1000 |
| | | Hawaii (HI) | 1000–2000 |

2000–3000 strains each for Argentina, Canada, China, Italy, Japan, Panama, Russia, and South Africa. The general trend is that many collections from a country/region preserve mostly strains from that region (Ecuador (CLQCA), Thailand (BCC, TBRC, TISTR), Slovakia (CCY), Slovenia (ZIM, EX), Ukraine (UCM), China (CGMCC) and most of the former USSR collections). The USA collections hold more than half of the strains obtained from the USA (Table 15.3). Many of the Argentinian strains are from the Libkind collection, and most of the

Brazilian strains are only preserved in the six Brazilian collections, with only a limited number kept in collections in other countries.

On the contrary, most European collections (e.g., CBS, BCCM/MUCL, CIRM, DSMZ, NCAIM, DBVPG, CECT) have a more evenly spread geographic distribution of strains; this is also true for the VKM (Russia) and JCM (Japan) collections. The NRRL (USA), UCDFST (USA), UWOPS (Canada), and UFS (South Africa) preserve many strains from their own country as well as from other countries.

## 15.5 Genera and Species Represented by Strains from Natural Environments

A challenge during this survey was to list the genera and species and estimate the number of strains linked to them in the participating collections. Many name changes occurred in the past few years, especially for the basidiomycetous yeasts (Wang et al. 2015a, b; Liu et al. 2015). Many collections have not yet updated the taxonomic affiliation of their strains, and it is possible that strains with only genus names associated were only based on preliminary identifications. Without a species epithet, it was not possible to know in which correct genus it belongs. This may have an effect on the number of strains in specific genera such as *Cryptococcus*, *Rhodotorula*, *Pichia*, and *Candida*. It is also good to keep in mind that different methods were used to identify the strains in the collections. Not all strains are yet identified using rDNA sequencing as some are only identified on physiological characteristics. This may also have an effect on the data presented here, especially at the species level.

According to the data obtained, most of the strains found in nature and preserved in the participating culture collections are affiliated with ascomycetous genera (Table 15.4). Well-defined genera that are abundantly found are *Clavispora*, *Cyberlindnera*, *Debaryomyces*, *Hanseniaspora*, *Lipomyces*, *Meyerozyma*, *Saccharomyces*, and *Sporopachydermia* with 500–1000 strains each and *Metschnikowia* within the 1000–2000 strain range. Most of the species are well distributed among the different collections except for *Clavispora*, *Metschnikowia*, and *Sporopachydermia* strains which are abundantly found in the UWOPS collection; the *Aureobasidium* strains are mostly from the EX collections, whereas *Lipomyces* strains are found in large numbers in the UFS collection. Almost all strains of the species *Saccharomyces eubayanus*, one of the most common species found of *Saccharomyces* during this survey, are preserved in the Libkind collection. It is possible that many of the strains currently identified as *Cryptococcus* sp., *Rhodotorula* sp., *Pichia* sp., and *Candida* sp. from the different collections may be changed to other or newly described genera when species names are updated in conformity with recent taxonomic revisions. Some but not all collections have made these updates, so it is unfortunately not possible to take that into account for this survey. Interestingly, many of the human pathogenic *Candida* species,

**Table 15.4** Overview of the number of strains per genus and the most abundant species present in the contributing collections

| # of strains per genus[a] | Genera | Most abundant species[b] |
|---|---|---|
| 10–30 | *Bannozyma*; *Bensingtonia*; *Botryozyma*; *Brettanomyces*; *Bulleribasidium*; *Bulleromyces*; *Carlosrosaea*; *Citeromyces*; *Colacogloea*; *Curvibasidium*; *Danielozyma*; *Derxomyces*; *Diddensiella*; *Dipodascopsis*; *Effuseotrichosporon*; [c]*Endomyces*; [c]*Farysia*; *Fellomyces*; *Fibulobasidium*; *Glaciozyma*; *Groenewaldozyma*; *Holtermanniella*; *Kockovaella*; [c]*Kondoa*; *Martiniozyma*; *Meira*; *Middelhovenomyces*; *Moniliella*; *Mrakia*; *Nadsonia*; *Nakaseomyces*; *Naumovozyma*; *Occultifur*; *Saccharomycodes*; *Sakaguchia*; [c]*Saprochaete*; *Schizoblastosporion*; *Sterigmatomyces*; *Symmetrospora*; *Tausonia*; *Teunomyces*; *Tilletiopsis*; *Trigonopsis*; [c]*Ustilago*; *Vanderwaltozyma*; *Zygoascus* | |
| 30–50 | *Cutaneotrichosporon*; *Cystobasidium*; *Dekkera*; *Diutina*; *Eremothecium*; *Kloeckera*; *Lodderomyces*; *Millerozyma*; *Moesziomyces*; *Peterozyma*; *Priceomyces*; *Rhodosporidium*; *Solicoccozyma*; *Spathaspora*; *Spencermartinsiella*; *Tetrapisispora*; *Trichomonascus*; *Zygotorulaspora* | |
| 50–100 | *Ambrosiozyma*; *Bullera*; *Cystobasidium*; *Cystofilobasidium*; *Dipodascus*; *Filobasidium*; *Issatchenkia*; *Leucosporidiella*; [c]*Magnusiomyces*; *Naematelia*; *Phaffomyces*; *Sporidiobolus*; *Suhomyces*; *Tortispora*; [c]*Tremella*; *Udeniomyces* | |
| | *Goffeauzyma* | *Goffeauzyma agrionensis* |
| | *Kregervanrija* | *Kregervanrija fluxuum* |
| | *Phaffia* | *Phaffia rhodozyma* |
| | *Yarrowia* | *Yarrowia lipolytica* |
| 100–150 | *Apiotrichum*; *Dioszegia*; *Geotrichum*; *Hannaella*; *Nakazawaea;* *Saccharomycopsis*; *Saturnispora*; *Sugiyamaella* | |
| | *Hyphopichia* | *Hyphopichia burtonii* |
| | *Komagataella* | *Komagataella pastoris* |
| | *Kuraishia* | *Kuraishia capsulata*; *Kuraishia molischiana* |
| | *Kwoniella* | *Kwoniella heveanensis* |
| | *Leucosporidium* | *Leucosporidium scottii* |
| | *Naganishia* | *Naganishia albida* |
| | *Rhodosporidiobolus* | *Rhodosporidiobolus ruineniae* |
| | *Starmera* | *Starmera caribaea* |
| | *Vishniacozyma* | *Vishniacozyma victoriae* |

(continued)

**Table 15.4** (continued)

| # of strains per genus[a] | Genera | Most abundant species[b] |
|---|---|---|
| 150–200 | [c]*Aureobasidium* | *Aureobasidiummelanogenum*; *Aureobasidium pullulans* |
| | *Blastobotrys* | *Blastobotrys parvus* |
| | *Galactomyces* | *Galactomyces geotrichum* |
| | [c]*Hortaea* | *Hortaea werneckii* |
| | *Kurtzmaniella* | *Kurtzmaniella cleridarum* |
| | *Myxozyma* | *Myxozyma mucilagina* |
| | *Starmerella* | *Starmerella meliponinorum* |
| | *Yamadazyma* | *Yamadazyma mexicana*; *Yamadazyma scolyti* |
| 200–300 | *Barnettozyma* | *Barnettozyma californica* |
| | *Pseudozyma* | *Pseudozyma hubeiensis* |
| | *Schwanniomyces* | *Pseudozyma polymorphus* var.*africanus*; *Pseudozyma vanrijiae* |
| | *Sporobolomyces* | *Sporobolomyces ruberrimus* |
| | *Wickerhamiella* | *Wickerhamiella australiensis*; *Wickerhamiella occidentalis* |
| | *Zygosaccharomyces* | *Zygosaccharomyces bailii*; *Zygosaccharomyces rouxii* |
| 300–400 | *Kazachstania* | *Kazachstania exigua*; *Kazachstania pintolopesii*; *Kazachstania unispora* |
| | *Ogataea* | *Ogataea polymorpha* |
| | *Saitozyma* | *Saitozyma podzolica* |
| | *Trichosporon* | *Trichosporon asahii* |
| | *Vanrija* | *Vanrija humicola* |
| 400–500 | *Cryptococcus* | |
| | *Kodamaea* | *Kodamaea anthophila*; *Kodamaea ohmeri* |
| | *Lachancea* | *Lachancea fermentati*; *Lachancea kluyveri*; *Lachancea thermotolerans* |
| | *Papiliotrema* | *Papiliotrema flavescens*; *Papiliotrema laurentii* |
| | *Scheffersomyces* | *Scheffersomyces stipitis* |
| | *Torulaspora* | *Torulaspora delbrueckii* |
| | *Wickerhamomyces* | *Wickerhamomyces pijperi* |
| 500–1000 | *Clavispora* | *Clavispora lusitaniae*; *Clavispora opuntiae* |
| | *Cyberlindnera* | *Cyberlindnera fabianii*; *Cyberlindnera subsufficiens* |
| | *Debaryomyces* | *Debaryomyces hansenii*; *Debaryomyces nepalensis* |

(continued)

**Table 15.4** (continued)

| # of strains per genus[a] | Genera | Most abundant species[b] |
|---|---|---|
| | *Hanseniaspora* | *Hanseniaspora guilliermondii*; *Hanseniaspora opuntiae*; *Hanseniaspora thailandica*; *Hanseniaspora uvarum* |
| | *Kluyveromyces* | *Kluyveromyces lactis*; *Kluyveromyces marxianus* |
| | *Lipomyces* | *Lipomyces starkeyi*; *Lipomyces tetrasporus* |
| | *Meyerozyma* | *Meyerozyma caribbica*; *Meyerozyma guilliermondii* |
| | *Saccharomyces* | *Saccharomyces cerevisiae*; *Saccharomyces eubayanus*; *Saccharomyces paradoxus* |
| | *Sporopachydermia* | *Sporopachydermia cereana* complex |
| 1000–2000 | *Metschnikowia* | *Metschnikowia borealis*; *Metschnikowia continentalis*; *Metschnikowia gruessii*; *Metschnikowia hawaiiensis*; *Metschnikowia ipomoeae*; *Metschnikowia koreensis*; *Metschnikowia lochheadii*; *Metschnikowia pulcherrima*; *Metschnikowia reukaufii*; *Metschnikowia santacecilia* |
| | *Rhodotorula* | *Rhodotorula mucilaginosa*; *Rhodotorula paludigena* |
| >3000 | *Pichia* | *Pichia deserticola*; *Pichia cactophila*; *Pichia heedii*; *Pichia kluyveri*; *Pichia kudriavzevii*; *Pichia membranifaciens*; *Pichia norvegensis* |
| >6000 | *Candida* | *Candida albicans*; *Candida apicola*; *Candida boidinii*; *Candida glabrata*; *Candida intermedia*; *Candida natalensis*; *Candida orthopsilosis*; *Candida parapsilosis*; *Candida parazyma*; *Candida sake*; *Candida sonorensis*; *Candida tropicalis* |

[a]Different methods were used to identify strains
[b]Most abundant species were only indicated when the number of strains of a species was more than 50 and more than 100 for *Candida* and *Pichia* species
[c]Genera and species data not included in yeast data of all collections

namely, *Candida albicans*, *Candida glabrata, Candida parapsilosis*, and *Candida tropicalis*, are often isolated from natural ecosystems other than from humans. Two *Pichia* species that are commonly found in extreme warm environments are *P. cactophila* and *Pichia deserticola*, two of the most frequently found species of this genus during this survey.

There are some genera included in Table 15.4 that not all of the participating collections supplied data for, as many of the curators categorize them as dimorphic or filamentous fungi rather than yeast (e.g., *Aureobasidium, Endomyces, Farysia, Kondoa, Magnusiomyces, Saprochaete, Tremella, Ustilago*), so the actual numbers of strains preserved in the collections for these genera may be much higher than indicated in Table 15.4.

## 15.6 Concluding Remarks

Although the number of participating collections only represents a small portion of the total number of collections worldwide preserving yeast strains, the presented data give a good indication of what type of strains is preserved to allow innovation and discovery by future generations. It is clear that yeasts have a wide range of habitats, from the cold Antarctic regions to the hot and dry deserts. The close association of yeasts with insects and plants and survival of yeasts in soil, fresh, and salt waters that is documented through the scientific studies described in other chapters of this book is supported by this survey. Furthermore, some culture collection online catalogs as well as GCM list publications associated with specific yeast strains, which allows researchers to more easily find ecological information associated with specific yeast strains.

The strains included in this survey were obtained from countries all over the world. However, it is clear that many regions such as the tropical lowland rainforests in the Amazon, Indonesia, and Central Africa; Arabian, Chinese, and Australian deserts; the arctic forests and tundras in Eurasia; and montane and submontane ecosystems, such as those present in the Himalaya, the Rockies, and the Andes are still underrepresented (this survey, Kurtzman et al. 2015). These surveys show that the close collaboration between depositors of yeasts and the worldwide culture collections is making excellent progress in preserving yeast biodiversity for future generations. The numbers of species presented in this survey are unfortunately only a drop in the ocean when compared to the predicted number of yeast species globally (Lachance 2006; Kurtzman et al. 2015), either waiting to be isolated, or isolated by not yet properly named, or already isolated and properly named but not preserved for future studies. The lack of suitable databases to facilitate data queries for specific data was one of the biggest obstacles encountered in this survey. The need for effective and public databases, whether local or as part of international efforts such as GCM, will become more urgent with emerging globalization.

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