

The rise of mycology in Asia

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ABSTRACT: Mycology was a well-studied discipline in Australia and New Zealand, Europe, South Africa and the USA. In Asia (with the exception of Japan) and South America, the fungi were generally poorly known and studied, except for the result of forays from some American and European mycologists. However, in the last 20 years, the situation has changed. With the development of Asian economies, the funding for science research and development has greatly increased. Mycological research has also diversified in many fields. Many studies have focused on applied aspects and new journals and websites have been established as a platform for Asian mycologists to publish their research. This paper will briefly review the history of the study of fungi in Asia and then discuss how it advanced during the last two decades. It will examine the current situation using case studies in plant pathogens, terrestrial saprobes, aquatic fungi, evolution studies, genomics and applied mycology and biotechnology. Finally, it will suggest research that is needed in the future.

KEYWORDS: Asian mycology, fungal diversity and evolution, genomics and applied mycology, mycological websites and journals

INTRODUCTION

The diversity of fungi is immense and yet less than 10% have been described [1, 2]. Fungi have unique attributes and are essential for the well-being of ecosystems as decomposers, mutualists, and pathogens. They also have huge biotechnological potential in agriculture (biocontrol agents, biofertilizers, growth-promoting hormones and pathogens), and as sources for many other industries such as biofuel, beverages, cosmeceuticals, food, mycoremediation, and pharmaceuticals [3]. Fungi being cosmopolitan, grow almost everywhere; mostly in terrestrial and aquatic habitats, and even in extreme environments, in deep sea vents, on rocks, plants,

soil, mosses, man-made materials and or associated with other organisms [3]. According to the state of world fungi report in 2018, the estimated number of fungal species on earth is between 2.2–3.8 million [4]. Due to the increased use of molecular-based techniques, specifically DNA-based, the rate of description of new fungal species has increased to more than 2000 species per year. These discoveries represent taxa mainly from Ascomycota, followed by Basidiomycota. In 2017, the majority of new fungal species were recorded from Asia, accounting for 35%, followed by Europe, Oceania, South America, North America, and Africa [4]. These numbers reflect the areas where most fungal taxonomists

work. For example, among these, the majority of the records were from China, Australia ranks second, followed by Thailand [4]. Asian mycologists are taking the initiative to actively participate in the ongoing quest to explore fungi and their applications. Most Asian regions have tropical and subtropical climates, where fungi thrive due to the favourable temperatures and humidity. Therefore, this region has a rich fungal diversity. In recent years, many young mycologists and fungal taxonomists have been trained in Asia and they are providing significant contributions to improve mycology in their respective countries.

This paper briefly reviews the history of mycology in Asia before the 20th century and addresses the current status of mycology. We provide case studies in plant pathology, aquatic fungi, terrestrial saprobes, evolution studies, genomics and applied mycology and biotechnology. We will suggest future areas of research needed in mycology in Asia.

Mycology before the 20th century in Asia

Half of the world's population lives in Asia, but many countries were economically disadvantaged and lacked resources for establishing laboratories for fungal research. Taxonomic studies of Asian fungi were limited because of reliance on overseas expertise, lack of local centers, language and a poor understanding of fungi by the public. In most of Asia (except Japan), fungal studies were carried out by visiting scientists or expatriate experts in the 18th and most of the 19th centuries. For example, an Irish mycologist, E.J. Butler contributed significantly to establish the foundation for mycology and plant pathology in India [5]. Visiting mycologists M.J. Berkeley, C.E. Broome and T. Petch contributed significantly to mycology in Sri Lanka. Their contributions increased the recorded number of fungi to over 2000 described species belonging to 640 genera. The eminent botanist and mycologist, E.J.H. Corner made remarkable contributions to the South-East Asian macrofungi, mainly in Malaysia and Singapore [6]. Most mycological laboratories employed conventional techniques, resulting in lower numbers of novel discoveries and publications. These reasons challenged the establishment of a successful mycological community in most of Asia. Due to isolation from the western world, Japanese mycologists and phytopathologists, however, published accounts of Japanese fungi during this period [7]. With the help of visiting scholars, however, several laboratories were set up in some parts of Asia in the latter part of the 19th century

(e.g., Thailand). The development of mycology in Thailand and Malaysia has been documented by Jones et al [6,8]. In Thailand, the enthusiasm of M. Tantichareon in establishing workshops and annual conferences and many international conferences, did a great deal to stimulate investigations of tropical fungi. Tzean et al [9] published five volumes on the Fungi of Taiwan with descriptions and excellent illustrations thus contributing to our knowledge of this region, and establishing an active Mycological Society.

During the latter part of the 1900s, Asia established societies to promote mycology. For example, the Indian Mycological Society was established in 1954. Among the 49% of the new fungal species (including fossils) introduced from 1981–1990 by the tropical countries, 9.7% were contributed by India and was ranked second to the USA, which contributed 10.1% of new species [10]. China, being the second largest country in Asia, carries a significant history of mycology which runs back to 1245 [4, 11] when the first monograph of Chinese fungi was published with 15 fungal species. During the 19th century, several projects such as the Comprehensive Scientific Expeditions in the Qinghai-Tibet Plateau (1973–1983), the Bioresources Survey and Evaluation (1988–1990) and many more individual investigations advanced the knowledge in the region. However, until the beginning of the 21st century, fungal species identification in China as well as in most parts of Asia was based mainly on morphological characters and sometimes on the geographical distribution [12]. The development of mycology in the region was therefore limited. Furthermore, Thailand, one of the more active countries for fungal research, mainly focused on applied mycology [13]. Much research was related to agriculture [13], while others focused on industrial applications, such as mushroom cultivation, citric acid soy sauce, alcohol fermentation, sweetened rice production, pigment production and biodeterioration [13]. Due to an increased interest and importance of mycology in the region, the International Mycological Association established a committee for Asia in 1977, later known as the Asian Mycological Association to promote mycology.

With the rapid development of DNA based techniques, molecular phylogenetic studies have advanced rapidly in Asian laboratories and used to study species diversity and systematics of many fungal groups [14–17]. Incorporation of molecular data into fungal research has allowed the extension of studies into diverse areas of life science, including

ecology, traditional taxonomy, phylogenetics, evolution, microbial community and chemotaxonomy, and mushroom cultivation [15, 18]. With the development of next-generation sequencing in the Asian region, specifically in China, many mycologists have adopted fungal genomics and transcriptomics approaches into their studies. This has opened new opportunities for mycologists to study the evolution or co-evolution of species, natural products discovery, biological control, medical mycology (disease mechanisms and virulence factors), host-fungal interactions, bioremediation, bio-fuel production, and genetic engineering of fungal strains for industrial purposes [19]. As a result, many publications in the above-mentioned fields came from the Asian region, especially from China [20, 21].

China, being the largest country in the region, has made significant advances in mycology. A large number of studies have been conducted in China in the 20th century, resulting in more than 6700 fungal species [4, 22]. China is the world's largest edible mushroom producer with an estimated annual yield of 38.42 million tons, accounting for around 75% of the global demand [4]. With the increased demand, research on the mushroom industry has accelerated in China. This has influenced other countries to focus on the mushroom related research [4].

The increased interest in mycology in the region has also led to an increase in journals published out of Asia (Table S1). The number of publications in taxonomic mycology from Asian in 1999 was 117, with an estimated 32 active taxonomic mycologists. These numbers have rapidly increased until the present day. China, Japan and Thailand have taken the lead in publishing in the Asian region with 427, 125 and 94 SCI articles published in 2019. India, Taiwan and South Korea have also contributed to a lesser extent. Fungal research has increased greatly in Thailand, with Mae Fah Luang University ranked first in the world for Mycology by CWUR World University Rankings 2019 (<https://cwur.org/2017/subjects.php#Mycology>).

Website development

Online databases serve as a repository for published data and several are being developed in Asia. These websites are dedicated to updating the taxonomy, classification or distribution of fungi. Currently, four webpages deal with different taxonomic groups (www.basidio.org, www.coelomycetes.org, www.dothideomycetes.org, www.sordariomycetes.org), while two webpages are dedicated for ecology and taxonomy (www.freshwaterfungi.org, [\[marinefungi.org\]\(http://marinefungi.org\)\), all providing illustrations and plates of fungal species and genera. The websites provide up-to-date outlines and accounts on orders, families, genera, and species levels, keeping abreast of the current literature. Other websites are: \[www.onestopshopfungi.org\]\(http://www.onestopshopfungi.org\) which provides a stable platform for the taxonomy of plant pathogenic fungi and related organisms. It combines all molecular data \(phylogenetic analyses, DNA sequence accession numbers\), recommendations on correct names, data on type material, geographical and ecological observations, ecological and economic significance, industrial relevance, and literature into a comprehensive and uniform treatise, so that fungal taxa can be identified. The website \[www.facesoffungi.org\]\(http://www.facesoffungi.org\) provides descriptions, photoplates, keys for identification, phylogenetic analyses, sequence accession data and ecological and economic significance of registered taxa. The website \[www.outlineoffungi.org\]\(http://www.outlineoffungi.org\) provides an up-to-date classification for all fungi and fungi-like organisms, while \[www.fungalgenera.org\]\(http://www.fungalgenera.org\) provides a short account of all accepted fungal genera of Ascomycota, Basidiomycota, and Lower Fungi with links to data.](http://www.</p>
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Mycological journals in the Asian region

With the increased interest in mycology, there are about 34 mainstream journals which publish mycological research in 2011. Besides these, several regional journals, plant pathology journals and many bulletins of national mycological societies publish research articles. Many new mycological journals have been introduced from the Asian region and some have SCI recognition. The mainstream peer-reviewed journals devoted to mycology are given in Table S1.

Major advances by Asian mycologists

There has been a great increase in mycological research and publications from Asian institutes and universities, while formerly strong research groups were found in Japan and Taiwan. Prominent examples are Beijing Forestry University (1955–present), BIOTEC, Bangkok (1995–present), Chiang Mai University (1996–present), The University of Hong Kong (1994–2008), Mae Fah Luang University, Chiang Rai (2009–present), Institute of Mycology & Lichenology, CAS, Beijing (1988–present), Kunming Institute of Botany (1989–present) and National Taiwan Ocean University (2008–present). Dai et al [23] showed that many more fungal taxa were being described from China, while Hyde et al [24] showed that the fungal diversity in

northern Thailand was remarkably high, with up to 93% of some genera (e.g. *Agaricus*) being new to science.

Asia has been leading the way in many areas of mycology and in particular in understanding fungal classification. Some of the most significant papers are *Families of Dothideomycetes* [25], *Taxonomy and phylogeny of hyaline-spored Coelomycetes* [26], *Notes for genera: Ascomycota* [27], *Outline of Ascomycota: 2017* [28], *Notes, outline and divergence times of Basidiomycota* [29], *Refined families of Sordariomycetes* [30], *Notes for genera: basal clades of fungi (including Aphelidiomycota, Basidiobolomycota, Blastocladiomycota, Calcarisporiellomycota, Caulochytriomycota, Chytridiomycota, Entomophthoromycota, Glomeromycota, Kickxellomycota, Monoblepharomycota, Mortierellomycota)* [31] and *Outline of the fungi and fungi-like taxa* [32]. These texts are incredibly important to students and young mycologists, providing classifications of most groups of fungi. The various series, Fungal Diversity notes and Mycosphere notes with 50 or more taxa, many new to science, treated in each paper and also mostly by Asian mycologists.

The fungal diversity of China, Malaysia and Thailand, where the main research has taken place, are still poorly known. In Malaysia, Chip [33] list 861 fungi, while Lee et al [34] list circa 3000. Thailand has more than 6000 known species of fungi and between 2009–2020 Hyde and coworkers have described 700 new species mostly from northern Thailand. Yet collections have been from many new habitats, hosts or areas, with numerous new species documented, including those in new genera, families and orders [4, 24]. The bottleneck in describing these new species is the lack of students for the necessary detailed morphological and phylogenetic studies and ability to obtain molecular data. Case studies in plant pathogens, terrestrial saprobes, aquatic fungi, evolution studies, genomics and applied mycology and biotechnology, where Asians have advanced mycology, are provided.

Plant pathogens

Asian mycologists have contributed a great deal to the understanding of plant pathogenic genera during the past two decades. Many of these mycologists worked on complex pathogenic genera, such as *Bipolaris-Curvularia*, *Colletotrichum*, *Diaporthe* and pestaloid taxa, establishing guidelines for species delimitation [35–40]. Cai et al [35] proposed that in order to correctly identify *Colletotrichum* to species level, a polyphasic approach is better than using

morphology alone. Later, it was established that this concept can be used for all the complex genera, leading to a new process to understand these complex fungi. Following the same concept, Cai and colleagues advanced the understanding on other plant pathogenic genera and recommended genes to provide a better resolution. Maharachchikumbura et al [38] took the initiative to identify the morphology, phylogeny and biochemistry of an important plant pathogenic genus, *Pestalotiopsis*. They tested ten gene regions to establish the best gene combination (ITS-Tub2-TEF1) for a better species resolution. Later, they segregated two novel genera from *Pestalotiopsis*, namely *Neopestalotiopsis* and *Pseudopestalotiopsis* based on molecular and morphological approaches [41]. Udayanga et al [40] assessed eight gene regions to establish the best gene combination for resolving *Diaporthe* species. In their study, the Genealogical Concordance Phylogenetic Species Recognition (GCPSR) concept was applied to resolve species boundaries based on individual and combined analyses of seven genes (except ITS), resolving the *D. eres* species complex. Manamgoda et al [39] revised the boundaries between *Bipolaris* and *Curvularia*. In their study, they accepted 47 species in *Bipolaris* and clarified the taxonomy, host associations, geographic distributions and species' synonymies. Another major contribution of Asian mycologists to the field of plant pathology is the starting of a paper series *one stop shop*. Hyde et al [42] initiated this concept to provide all the information, such as history of the disease, symptoms, life cycle, on plant pathogenic fungal genera in one place which has provided easy access to plant pathologists to all the relevant information on a specific plant pathogenic genus. OSS2 and OSS3 detailing 50 pathogenic genera have since been published [43].

Asian mycologists have contributed enormously in the establishment of a stable taxonomy of the pathogenic genus *Colletotrichum*. Hyde et al [36] provided the first ever most comprehensive overview of the genus with 66 common names in use and 19 doubtful names. Another article published by the same author highlighted the importance of revising the genus by using molecular methods. These studies are the foundation of the still ongoing revision of the genus based on multi-locus sequence data. Cai et al [35] introduced the use of polyphasic approaches in identifying this group of fungi. Mycological groups led by K.D. Hyde and L. Cai have introduced many species of *Colletotrichum* based on not only concatenated

loci, but also with the application of GCPSR. Jayawardena et al [44] provided an account of *Colletotrichum* accepting 190 species, with a backbone phylogenetic tree and notes for each species.

Diaporthe is another plant pathogenic genus that the Asian mycologists have contributed immensely to clarify the taxonomy. Through his studies, Udayanga et al [40] contributed in understanding species delimitation in this genus. Many Asian mycologists also contributed in identifying the species on economically important plants and forest plants [45]. Gao and collaborators showed that this genus is paraphyletic. Dissanayake et al [45] provided accounts for 171 accepted species with a backbone tree for the genus. Manawasinghe et al [46] contributed to the understanding of this genus by studying the high genetic diversity and species complexity of *Diaporthe* associated with grapevine dieback.

Botryosphaeriaceae is a family of plant pathogenic fungi and many Asian mycologists have contributed to the understanding of the genera. Liu et al [47] used a phylogenetic approach together with a study of herbarium specimens and provided detailed accounts of the accepted genera in this family. Dissanayake et al [48] provided a backbone phylogenetic tree for the family and notes on accepted genera and species.

Terrestrial saprobes

Dead plant material is mainly decomposed by fungal saprobes including ascomycetes, basidiomycetes and basal fungi. They are essential for nutrient cycling and are the major decomposers of lignin [3]. Asia has provided major advances in describing many of its fungi. Hyde et al [24] showed that 96% of *Amanita* and 93% of *Agaricus* species collected in mainly northern Thailand were new to science. Other important contributions were monographs of Boletales [49] and *Amanita* [50] and studies on Polyporaceae [51] and advances in the genus *Agaricus*. However, perhaps the most important advance was the notes and an outline to all Basidiomycota [29].

The study of microfungi is, however, in its infancy. Research on the microfungi on bamboo [52], teak [53] and Pandanaceae [17] provides preliminary knowledge, but certainly did not describe all taxa from these hosts. Zhang et al [54] reported 246 species in 116 genera from two unnamed Karst cave in Guizhou, China, including 20 new species. This first study is followed by a second

Table 1 Fungal taxonomic novelties from Asian aquatic environment.

Orders/Families	Genera	Species
Orders	<i>Halodiatrype</i>	<i>Bacusphaeria nypae</i>
Distoseptisporales	<i>Striatiguttula</i>	<i>Fusicolla bharatarvarshae</i>
Dyfrulomycetales	<i>Bacusphaeria</i>	<i>Halodiatrype avicenniae</i>
Jahnulales	<i>Thyridariella</i>	<i>Striatiguttula nypae</i>
Families	<i>Halotestudina</i>	<i>Thyridariella mangrovei</i>
Striatiguttulaceae	<i>Gesasha</i>	
Distoseptisporaceae		
Ceratosphaeriaceae		
Triadelphiaceae		
Dyfrulomycetaceae		

paper [55] which reported 2344 strains belonging to 610 species in 253 genera and introduced 33 new species. Mapook et al [56] described the fungi on Siam weed, a species from Central America. Remarkably, one family, 12 genera and 47 species were new to science and must have jumped to this host from surrounding hosts. Preliminary studies on the fungi on seeds and fruits resulted in eight new genera and 65 new species [57, 58]. In fact, the fungi on most terrestrial hosts in Asia have barely been studied and we predict that tens of thousands of species await discovery.

Aquatic mycology

The majority of the research on aquatic fungi in recent years has been from Asia and studies have incorporated molecular techniques to achieve a better classification of taxa. As a result, over 500 new species and some new genera, families and orders (Table 1) have been introduced [15, 27, 28, 30, 54]. The Greater Mekong Subregion has been relatively well-explored for freshwater fungi [16, 59]. Most of the studies follow the direct observation of fruiting bodies on different substrates and use culture-dependent techniques [16]. There are few reports on the unculturable fungi in freshwater habitats in Asia [61], hence, culture-independent techniques need to be followed to understand the true diversity among freshwater fungi in Asia. For example, Kagami et al [61] analyzed the planktonic fungi in Lake Inba, Japan using denaturing gradient gel electrophoresis and revealed Chytridiomycota as the dominant group, followed by Basidiomycota and Ascomycota. However, it is not clear whether the resulting operational taxonomic units (OTUs) have any role or are spores present. A world monograph of all freshwater Sordariomycetes was published by Luo et al [16] and will be followed by one on Dothideomycetes.

The study of marine fungi in Asia has been

prolific and has predominantly been led by EBG. Jones who worked in BIOTEC, Thailand, University of Malaya, Malaysia and other Asian regions. Marine environments in Asia have been a genesis of many novel fungal taxa [62, 63], with molecular data being included in most studies. Countries with reports of new species of marine fungi over the past decade (2010–2019) are India [64], Japan [65, 66], Malaysia [67], Saudi Arabia [68, 69] and Thailand [63]. As a highpoint to his life's work, EBG. Jones has developed a website (www.marinefungi.org) on marine fungi with his Asian colleagues [70]. Besides taxonomic studies, marine fungi have also been studied as a source of biologically active compounds [71, 72].

Evolution studies

Knowledge of fungal evolution helps to provide an understanding of the diversity of life as similarities between species/higher-level taxa occur as heritable changes over time and in populations. Fungi in Asia are clearly highly diverse, especially in tropical Asia [24]. Although the numerous fungi discovered in Asia are morphologically and phylogenetically well-studied, there have been relatively few evolutionary studies. Mycologists have applied evolutionary study to understand fungi in different research disciplines. For example, the study of ancestral characters not only explains the evolution of morphology in fungal groups, but can also estimate the probability of ancestral habitat or nutritional modes. Co-evolution of plant-fungus relationships visualize how fungal species are ecologically linked, and how they co-evolved to survive in a specific time period [73]. The study of fungi which are resistant to fungicides through evolution is ongoing and may lead to methods to resolve this issue [74]. These studies are needed because of the extensive use of fungicides in Asia. According to evolutionary changes over time, which gives rise to new species, fungal evolution with divergence time estimation has been used for classification and ranking of fungi at higher levels [14, 75]. In these analyses, it is necessary to include a starting point for any molecular dating, paleoecological re-construction, and morphological character evolutionary study [18]. Hence, reliable fossils information of fungi is needed to define the boundary of estimation [18], and more sequence data of novel species are requested to accurate analyses.

Fungal evolution has become clearer with various Asian studies [15, 56, 62]. This is being improved by the introduction of higher taxa with sup-

port from evolutionary evidence. Despite the recent molecular clock dating of the Fungi [75] studies on co-evolution and evolution of fungal characters, further studies are needed.

Genomics

The genome provides a glimpse into the molecular basis of fungal biological diversity. Genome sequencing of fungi represents a significant milestone in mycology. Accelerated progress in sequencing technologies and bioinformatics enable access to genomes at rapidly reducing costs. Therefore, initiatives have been launched to sequence a wide range of fungal genomes [76]. Developments in the field of genomics have paved way for comparative genomics; this, in turn, benefits many fields including agriculture and biotechnology. In Asia, fungal genomics has received much attention from scientists in China, Japan, Korea, India, Iran and Thailand, where considerable investments in fungal genomics research have been made. China has taken the lead in Asia with many laboratories initiating fungal genomic projects [19], which have accelerated the pace of mycological research in China. Asia, in particular China, has focused on economically important fungi in many genome projects. The landscape of Asian genomic and functional genomic projects have concentrated on areas, such as plant and human pathogenic fungi [21], fungal-host interactions [77, 78], fungi as biocontrol agents [79], fungi as food [80] and medicinal fungi [20, 81]. Asian large scale sequencing bodies, such as Beijing Genomics Institute (China), Macrogen (Korea), Chun Lab (Korea), Softbank (Japan), Temasek (Singapore), Prenetics (Hong Kong), Xcode (India) and Genomico (Iran), have also been collaborating with large scale fungal genomic projects. The rapid development of bioinformatics infrastructures has facilitated a boom in Asian fungal genomics in the region [19, 82]. In addition, several mycological breakthroughs have been published by Asian scientists, such as massive decoding of non-model fungal genomes [19, 20] and successful application of *Agrobacterium*-mediated fungal transformation and CRISPR/CAS9 systems [83]. While China leads the way, many governments and private sectors in Asia are investing billions of dollars into genetics research. As genomics takes a firm hold in Asia, regulators will need to establish standards on the genetic data management.

Applied mycology and biotechnology

Applied mycology is a discipline where we use the full potential of fungi for industrial exploitation. Initially, applied mycology mainly focused on agriculture or where fungi caused damage. However, after several decades significant developments were made globally towards using fungi for new processes, and environmental-friendly products [3]. The trend for fungal genetic research has moved from genes to genomics, to functional genomics. In Asia, research on functional genomics of economically important fungal taxa has accelerated and this resulted in the accumulation of genetic information [77, 78]. The data are currently being used to enhance industrial processes and obtain value-added products, such as bulk manufacturing of organic acids, proteins, enzymes, secondary metabolites and active pharmaceutical ingredients [3].

A common application of mycology in Asia is for agricultural purposes. These applications can vary from using fungi as biocontrol agents, biofertilizers, mitigating abiotic stresses in plants and the production of biofungicides, insecticides, nematicides, herbicides and growth-promoting hormones [3, 84, 85]. Furthermore, fungal genes have been genetically engineered into plants to produce resistant varieties [86]. Owing to their antibiotic, antimycotic, antiviral, anticancer, antidiabetics and immunosuppressive properties, there have been many studies in Asia to assess the potential of fungi in the pharmaceutical industry [3, 87]. In addition, fungi have been used in Traditional Chinese Medicine and this practice is being used in Japan and other parts of Asia [3].

Domestication and industrial production of mushrooms occurs across Asia. China has the greatest global demand for food including mushrooms. Mushroom production in Asia has changed from manual to automated and also, novel hybridized strains are being developed mainly in China and Thailand [4]. Studies are also being conducted to genetically engineer or manipulate mushrooms for higher yields and longer shelf-lives [88, 89]. Apart from these applications, fungi are vastly used in Asian food and beverage industries as food colourants, bio-flavours, probiotics and in wine, beer and spirit production [3]. Furthermore, fungi have been used as a sustainable solution for many global problems [3]. For example, in many parts of Asia, agricultural waste has been recycled as substrates for mushroom production. In addition, fungi or their products have been utilized in pro-

cesses such as mycoremediation, mycofumigation, and fungal degradation of plastics and polycyclic aromatic hydrocarbons [3]. Studies to assess the genetic manipulation of these processes are being conducted. Asian industrial production of fungal-mediated biofuels, organic acids, cosmeceuticals, enzymes, and textile dyes are commonplace, but studies are needed to improve these processes [3].

Knowing the gene and protein function of beneficiary fungal traits has boosted the fungal biotechnology research arena. Bioengineering has dramatically improved yield, quality, resistance and the nutritional value of foods and also facilitates sustainable agriculture. Asia scientists have studied the heterogeneous expression of fungal secondary metabolite gene clusters [90], enabling the biosynthesis of antibiotics and natural products [3]. Applied mycology will continue to be the direct beneficiary of future advances in fungal genomics and fungal biotechnology. The progress achieved by Asia scientists in transferring basic mycology knowledge to applied mycology, and biotechnological applications during the last two decades has been impressive.

The future

Where does the future lead us? With tens of thousands of new species awaiting collection and description, there is so much research needed. However, the future challenge for the mycologists is not only to discover novel fungal taxa and understand their evolutionary relationships, but also discover potential diversities of dark taxa hidden in fungal sequences and place them into the tree of life. The knowledge gathered from these studies provides exciting opportunities for the molecular mycologists to predict fungal properties that can be exploited further. Such research may be basic, but it will provide us with the resources and tools for numerous applications. For example, new edible species of mushrooms can be commercialized and increase the variety of foods in the market. Medicinal mushrooms with anti-cancer and anti-diabetic properties can be commercialized and sold dried or fresh or packaged in teas or powdered capsules. The novel microfungi are likely to span across the kingdom fungi and thus provide a powerhouse of metabolic pathways that can be utilized in the industry as biofertilizers, biofuels, enzymes, organic acids, proteins, secondary metabolites, textile dyes, and active pharmaceutical and cosmeceutical ingredients. The aim of future fungal research should be to convert the results of these basic sciences to practical appli-

cations.

The accelerated pace of fungal genomics research and its development in the region has provided genomic resources for more than 1000 fungal species and resulted in a huge amount of data. Even though fungal genomics evolved rapidly, very few biotechnological developments resulted from *omics* sciences. The *omics* technologies such as functional genomics, transcriptomics, proteomics, metabolomics and interactomes are currently undergoing a development phase. Future studies using *omics* technologies should reveal information related to fungal adaptations, evolution, industrializations and fungal interactions. The future of Asian mycology depends on innovative studies focused on enhancing fungal metabolic processes or engineering industrially important fungi for maximum production. For mycology to thrive in this region, collaborations among Asian mycologists and improvements for bioinformatics infrastructures are necessary.

Appendix A. Supplementary data

Supplementary data associated with this article can be found at <http://dx.doi.org/10.2306/scienceasia1513-1874.2020.S001>.

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Appendix A. Supplementary data

Table S1 Mainstream Asian mycological journals.

Journal	Publisher	Reference
Asian Journal of Mycology ^{a,b}	CEFR, Mae Fah Luang Univ, Thailand	https://asianjournalofmycology.org
Current Research in Environmental and Applied Mycology ^{a,b,c}	Beijing Academy of Agriculture & Forestry Sciences, China	http://www.creamjournal.org
Fungal Diversity ^{b,c} (IF: 15.596)	Kunming Institute of Botany, CAS, China	https://www.springer.com/journal/13225
Fungal Science ^b	Mycological Society of Taiwan	http://mycology.sinica.edu.tw/TaiwanMycoSoc/Default.aspx
Kavaka ^a	Mycological Society of India	http://www.fungiindia.co.in/index.php
Medical Mycology Journal ^{a,b} (IF: 2.851)	Japanese Society for Medical Mycology	https://www.jstage.jst.go.jp/browse/mmj/-char/en
Mycobiology ^{a,c} (IF: 1.369)	Korean Society of Mycology	https://www.tandfonline.com/toc/tmyb20/current
Mycology ^{a,b,c} (IF: 0.56)	Chinese Mycological Society	https://www.tandfonline.com/toc/tmyc20/current
Mycoscience ^{b,c} (IF: 1.229)	Mycological Society of Japan	https://www.journals.elsevier.com/mycoscience
Mycosphere ^{a,b,c} (IF: 2.015)	Guizhou Academy of Agricultural Sciences, China	http://mycosphere.org
Mycosystema ^b	Mycological Society of China and Institute of Microbiology, CAS	http://manu40.magtech.com.cn/Jwx/CN/1672-6472/home.shtml
Plant Pathology and Quarantine ^{a,b}	Agriculture College, Guizhou Univ, China	http://www.plantpathologyquarantine.org
Studies in Fungi ^{a,b}	Institute of Animal Science, CAAS, China	http://www.studiesinfungi.org
The Korean Journal of Mycology ^{a,c}	Korean Society of Mycology	http://www.kjmycology.or.kr

^a Dielectric data obtained at room temperature and a frequency of 1 kHz

^b No publication costs

^c Scopus indexed journals