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A review on lichen diversity studies in Northeast Asia

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The Northeast Asian region is characterized by unique geographical and climatic conditions which harbor a rich diversity of lichens. Lichens in Northeast Asia are understudied as there is a lack of comprehensive studies synthesizing scientific knowledge on this group. This paper compiles a detailed historical overview of lichen research in various countries across Northeast Asia, including China, Japan, the Korean Peninsula, the Russian Far East, and Mongolia. The paper summarizes the current state of knowledge as well as future research trajectories on lichens for each country. We describe the inception of lichen research, major publications, key researchers and institutions involved in these studies, and a catalogue of lichens described in each nation.

KEYWORDS
biodiversity, checklist, lichens, Northeast Asia, species distribution

1 Introduction

Biodiversity is fundamental in ensuring the stability and operational efficacy of ecosystems and underpins the very fabric of human existence. Yet, this vital diversity is besieged by a multitude of grave threats, including habitat destruction, climatic flux, and rampant overdevelopment. These factors culminate in the alarming phenomena of species extinction and the degradation of ecosystems. The international community has awakened to the criticality of biodiversity preservation, responding to its diminution with the establishment of various international frameworks and conservational initiatives, notably the Convention on Biological Diversity (Secretariat of the Convention on Biological Diversity, 2006). In this context, an increasing number of nations are now bestowing an unprecedented level of attention to environmental conservation, cognizant of the manifold threats imperiling the natural world. Among the components of biodiversity, lichens emerge as a critical element in both research and the conservation of ecosystems, a fact that cannot be overstated (Wei, 2020). Lichens were long regarded as "plants." In fact, they are not composed of a single organism, but rather represent a mutualistic symbiotic complex formed by a symbiotic fungus (lichenized fungi) and photosynthetic partners (Chlorophyta or Cyanobacteria, and sometimes both) (Lücking et al., 2017). In biological classification systems, all organisms that form lichens have their own scientific names and phylogenetic positions. Among them, lichenized fungi exhibit high species diversity and belong to either the Ascomycota or Basidiomycota within the Kingdom Fungi, referred to as lichenized

ascomycetes or lichenized basidiomycetes, respectively. Globally, there are approximately 40 orders, 119 families, 1,002 genera, and 19,409 documented species of lichenized ascomycetes, accounting for about 34% of all known ascomycete species. In contrast, lichenized basidiomycetes are far less diverse, comprising only 2 orders, 2 families, 3 genera, and 50 species (Lücking et al., 2017). Consequently, known lichenized ascomycetes represent about 99.7% of all documented lichenized fungi (Ren, 2023). Their distinct physiological and ecological traits position lichens as vital ecological indicators, repositories of biological resources, and exemplars of ecological adaptability. The applications of lichens are diverse, ranging from desert biological carpet engineering (Wei, 2018) and biomonitoring (Abas, 2021) to the use of lichen-derived secondary metabolites in biopharmaceuticals and ultraviolet protection (Basnet et al., 2019), thus illuminating their indispensable value in specialized fields. Human activities have precipitated alterations in lichen habitats, raising the specter of extinction or endangerment for some species, potentially prior to their discovery or comprehensive study (Ren et al., 2019). Therefore, the exploration and scholarly investigation of lichens have become matters of pressing urgency.

Northeast Asia, sometimes called Northeastern Asia or Northeast Eurasia, is a geographical subregion of Asia. In biogeography, Northeast Asia generally refers roughly to the area spanning the Japanese archipelago, the Korean peninsula, the Mongolian Plateau, Northeast China, and the Russian Far East (Figure 1). Northeast Asia is mainly covered by temperate forest, taiga, and the Eurasian Steppe, while tundra is found in the region's far north. Summer and winter temperatures are highly contrasted. It is also a mountainous area. The region of Northeast Asia, distinguished by its rich ecological and biotic diversity, serves as a haven for a plethora of unique species and ecosystems. Current research indicates that the examination and surveying of plant flora in Northeast Asia are being pursued with vigor (Wang et al., 2023). However, when juxtaposed with the understanding of vascular plant biodiversity, the knowledge of lichen biodiversity in this region remains comparatively underdeveloped. Presently, lichenological studies in Northeast Asia remain in a nascent stage, with a conspicuous deficit of comprehensive, integrative research synthesizing the scientific corpus on this taxonomic group. Despite this, each country within Northeast Asia has contributed to the lichenological literature, evidenced by the publication of region-specific lichen floras (Golubkova, 1981; Chen, 2015; Harada, 2016a; 2016b; 2016c; 2016d; Hur et al., 2016; Belov et al., 2021). Moreover, exhaustive lichen catalogs have been compiled for all countries in Northeast Asia, save for the Russian Far East. Owing to geographical and historical factors, the lichens of these countries or regions are often collectively studied and compared (Asahina, 1939; Jørgensen, 2001; Kantvilas et al., 2005; Zhurbenko and Zheludeva, 2015). Japan pioneered lichen research in Northeast Asia, initiating studies in the 1930s and concurrently exploring lichens in East Asia alongside its domestic research efforts (Sato, 1941). In China, early lichenological investigations were largely undertaken by Japanese and Russian researchers. Mongolia's entry into lichen research occurred subsequently, with many seminal Mongolian lichen works authored by Russian lichenologists (Golubkova, 1981; 1983).

This literature review serves as a foundation for the synthesis of data pertaining to the diversity of lichen species, genera, and families within the Northeast Asian region. In the context of China, the analysis principally relied on *The Enumeration of Lichenized Fungi in China*. This comprehensive review elucidates the presence of 3,085 lichen species in China, categorized under 445 genera and 99 families (Wei, 2020). In Japan, the lichen biodiversity is quantified at 1,801 species, distributed among 389 genera and 133 families (Ohmura and Kashiwadani, 2018). For the Korean Peninsula, the data was sourced from the Standard Lichen Catalog of its National Species Information System, revealing a total of 1,189 species, systematically classified into 274 genera and 90 families. Mongolia's contribution to the lichen diversity encompasses 1,067 species, associated with 208 genera and 63 families (Byazrov, 2013).While a comprehensive lichen catalog for the Russian Far East is yet to be compiled, existing documentation for

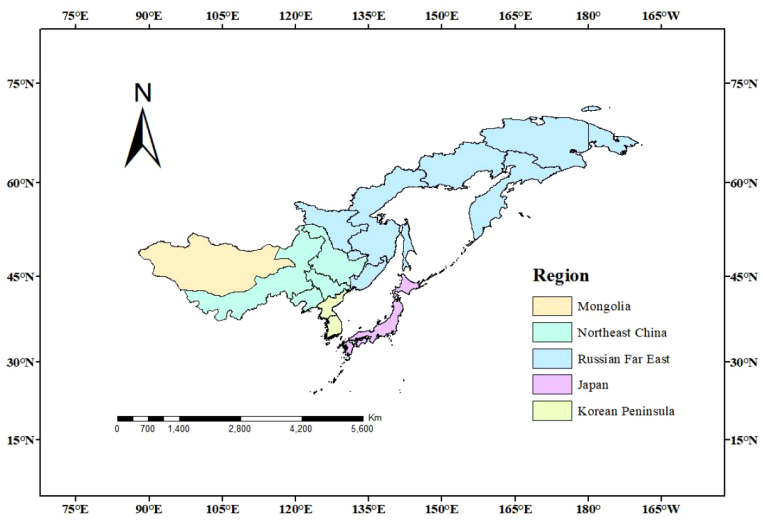

FIGURE 1
The region of Northeast Asia.

the southern part of this region records a significant count of 943 lichen species (Chabanenko, 2002). To date, a comprehensive and integrated catalog of plant diversity data remains elusive. The current study aims to provide an overview of the historical development of botanical research in Northeast Asian, highlighting significant contributions from individual countries within the region.

2 Lichen flora information in China

China, strategically situated in the eastern segment of Asia and bordering the western periphery of the Pacific Ocean, encompasses an expansive territory of approximately 9.6 million square kilometers. Its enormous expanse, ranking as the world's second-largest by land area, boasts a mosaic of diverse topographies, climatic conditions, and vegetation types. This multifaceted environment fosters an ideal habitat for a broad spectrum of lichen species. Lichens in China are ubiquitously distributed, thriving in varied ecosystems ranging from mountains to plains, forests to grasslands, and along rivers and lakes. As of current records, China is home to 3,164 identified species of lichenized fungi, constituting approximately 15.7% of the globally recognized lichen species.

The study of lichens in China dates back to ancient times, with mentions in historical texts such as The Book of Songs and later works by Chinese pharmacologists. European naturalists, particularly those from Sweden, Germany, and France, began collecting lichens in China in the 18th century, with subsequent contributions from scholars across Europe, America, and Japan. Notable collections and publications in the 19th and early 20th centuries laid the groundwork for Chinese lichenology. Chinese botanists became more involved in lichen research in the mid-20th century, leading to significant contributions in taxonomy and classification. From the late 20th century onward, comprehensive works like the *Flora Lichenum Sinicorum* and *Cryptogamic Flora of China* were established, providing a solid foundation for further studies on Chinese lichens. Research in Northeast China, particularly in regions like Changbai Mountain, Heilongjiang Province, and the Greater and Lesser Khinggan Mountains, has yielded valuable insights into the diversity and distribution of lichens in this area.

The earliest records of lichens in China appear in the ancient text *The Book of Songs*. During the Tang dynasty, Zhen Quan mentioned "Song Luo" (*Usnea* spp.) and "Shi Rui" (*Cladonia* spp.) in *Yao Xing Ben Cao*. Li Shizhen, a renowned Chinese pharmacologist, published *Ben Cao Gang Mu* in 1578, where he mentioned four types of lichens: "Shi Rui" (*Cladonia* spp.), "Di Yi Cao" (maybe refers to the lichens *Peltigera* spp. or *Lobaria* spp.), "Shi Er" (*Umbilicaria* spp.) and "Song Luo" (*Usnea* spp.). In the Qing dynasty, Zhao Xuemin described "Xue Cha" in *Illustrated Supplements to Compendium of Materia Medica*, which was believed to be a form of lichen known as *Thamnolia* sp. Although it is difficult to accurately identify the lichens described in these ancient documents, it is evident that lichens were utilized as herbal medicine and had a role in human society since ancient times (Chen, 2015).

Commencing in the 18th century, the study of lichens in China has been predominantly characterized by research on collections amassed by foreign naturalists, notably those from Europe, including naturalists, missionaries, and scientists. Additionally, there were contributions from scholars across Asia, particularly Japan, and notable botanists from the Americas, such as the United States. The majority of these collectors arrived via maritime routes, leading to a concentration of early lichen collections in coastal regions (Liu et al., 2011). Pehr Osbeck of Sweden was one of the pioneering collectors, followed by others from Italy, Austria, Germany, France, the United Kingdom, and Russia, who subsequently engaged in the collection and scholarly dissemination of works on Chinese lichens. The earliest record of lichens in China was reported by the Swedish scholar Osbeck in 1757 as *Lichen chinensis* Osbeck (Bretschneider, 1898). However, this designation was not validly published and referred to the species currently recognized as *Parmotrema tinctorum* (Dilese ex Nyl.) Hale (Hawksworth, 2004). In 1843, two Prussian collectors, Franz Meyen and Johann Flotow, published *Lichenes* (Meyen and Flotow, 1843), documenting three new lichen species collected in Macau and Guangzhou. Berthold Seemann, a German naturalist affiliated with Kew Gardens, acquired numerous plant specimens during the Herald's global expedition, and recorded three lichen species in the 1856 publication *Flora of the Island of Hong-Kong* (Seemann et al., 1852), which were collected in Hong Kong by Henry Fletcher Hance. Additionally, Gottlob Ludwig Rabenhorst of Germany, drawing from collections made by his son in Guangdong, Shanghai, and other regions over the preceding two years, produced *Chinesische Flechten*, documenting 36 species across 17 genera (Rabenhorst, 1873).

In 1892, the French collector Antoine Hue meticulously documented 77 Chinese lichen species previously recorded by William Nylander in the work *Lichenes Exotici* (Hue, 1892). Between 1901 and 1904, the distinguished Russian lichenologist Alexander Elenkin authored *Lichenes Florae Rossiae et Regionum Confinium Orientalium*, reporting over 200 species of lichens. This seminal work included 9 species collected by Grigory Potanin in Xikang (present-day Tibet) in 1893, and several species from Mongolia (Elenkin, 1901; 1904), In 1907, the French mycologist Narcisse Patouillard, in collaboration with Henri Olivier, published *Champignons et Lichens Chinois* (Patouillard and Olivier, 1907), reflecting the burgeoning interest in lichenological studies in China. Owing to this heightened interest, numerous institutions initiated large-scale lichenological expeditions in China, including the German Research Collection Expedition, the Austrian Academy of Sciences Expedition, and the Swedish Central Asian Scientific Expedition. These endeavors yielded extensive collections from various provinces in northwest China, such as Gansu, Tibet, Xinjiang, as well as in several southern provinces. The findings from these expeditions were extensively published in works like Across Asia Volume III, 1911, Essentials of Chinese Flora Volume III, Lichens, and in the Sino-Swedish Expedition's publications Lichens of Central Asia (Magnusson, 1940; 1944; Bohlin, 1949). In 1930, the Austrian lichenologist Alexander Zahlbruckner

documented a remarkable 430 species from southwest China, including 219 new species with type localities in China (Zahlbruckner, 1930). This work is heralded as a foundational study in Chinese lichenology and was referred to as a 'milestone in Chinese lichenology' at that time. Three years later, based on specimens collected by Asahina Yasuhiko in Taiwan as the core, and incorporating some collections by scholars such as Faurie, Ogata, and Sasaki, Zahlbruckner classified and named 81 genera and 260 species. Among them, approximately 100 species were published as newly described species by Masami Sato (Sato, 1938). In the late 20th century, Hannes Hertel and Zhao Chuanfeng significantly enriched the lichen flora of Northeast China with their study of lichens in the Changbai Mountains (Hertel and Zhao, 1982). Additionally, Teuvo Ahti et al. contributed to the lichenological record by publishing data on several new or newly distributed taxonomic units of Cladoniaceae and Usneaceae in China (Ahti et al., 1999). In the early 21st century, Hawksworth and Mariette assembled the inaugural checklist of Chinese lichens, based on an extensive literature review and additional field collections, thereby estimating the diversity of lichenized fungi in China (Hawksworth and Mariette, 2003).

Chinese botanists became more involved in lichen collection and research in the early 1930s. The first research literature on Chinese lichens by a Chinese botanist was *Rock Vegetation of Zhongshan, Nanjing* published in 1932 by Qian Chongshu. Three years later, Zhu Yancheng published *Preliminary Study of Chinese Lichens*, recording 43 species, 12 varieties, and 17 genera of lichens from across ten provinces of North China. In the early stages, lichen identification in China was still carried out by foreign scholars. Lichens were collected by many researchers (such as Liu Shenye, Zhu Yan cheng, Hao Jingsheng) across Beijing, Hebei, Shandong, Zhejiang, Hong Kong, Xinjiang, Jilin, Shaanxi, Suiyuan, Liaoning, and were then sent to France for identification (Moreau and Moreau, 1951). After 1949, more Chinese lichenologists began studying and identifying lichens from their own country, marking a new phase of Chinese-led research on native biodiversity. In 1955, Zhou Ying's publication *Lichens* gave Chinese readers a Chinese-written, comprehensive introduction to lichen plants for the first time. Other Chinese researchers began to share their publications on Chinese lichens: Lu Dingan published Miscellaneous Records of Chinese Lichens 1: Genus Diploschistes and Miscellaneous Records of Chinese Lichens 2: Family Umbilicariaceae in 1958 and 1959, respectively, and in 1960, an article on the economic uses of lichens. Wu (1963); Chao (1964); Wei (1966), and others furthered these efforts and published significant research on Chinese lichens classification and taxonomy.

Starting in the 1970s, the study of lichens in China entered a period of rapid development, with the establishment of the Editorial Committee of the Flora of Chinese Spore-producing Plants by the Chinese Academy of Sciences. Cryptogamic Flora of China, a comprehensive work on the classification and ecology of spore-producing plants, remains as a crucial reference for understanding biodiversity, resource utilization, and species conservation (Tian, 1998). So far, Cryptogamic Flora of China has published 117 volumes to include the expansion of lichen knowledge, and *Flora Lichenum Sinicarum* has published 6 volumes incorporating updated information. Since lichenology in China is a relatively young field, *Flora Lichenum Sinicarum* had a relatively weaker foundation and only began to be published sequentially in the 21st century (Tian, 1998). The publication of *Flora Lichenum Sinicarum* provides continual updates and supplements to lichenological knowledge, such as by improving classification systems and updates species names when new findings are made. By compiling the known research on lichens as well as actively updating the field of information, this work is fundamental to understanding biodiversity and utilizing lichen resources. Flora Lichenum Sinicarum is especially important in the study of Chinese lichen species, thus marking a milestone in the study of lichenology in China.

Starting from the early 1960s, Ma Ji compiled and published The Checklist of Chinese Lichens (Volumes I-X) over a period of about twenty years, after accumulating samples and making international research collaborations. Ma's series represents the first lichen checklist published in China (Ma, 1981). In 1982, Zhao Jiding and others collected lichen specimens in Yunnan, Guangxi, Hunan, Sichuan, Anhui, and Hubei, combining these with other samples to publish Preliminary Compilation of Chinese Lichens. The guide introduces 214 lichen species, each with detailed morphological descriptions (Zhao, 1982). Iconography of Chinese Lichen (Wu, 1987), provides basic knowledge of 351 common Chinese lichen species, including hierarchical classification tables and color photographs. This handbook serves not only as a reference for botanists but also assists students and teachers as well as forestry and environmental protection professionals in lichen conservation and identification. Wei Jiangchun is a prominent pioneer in Chinese lichenology and has published 115 papers and works to date. The Enumeration of Lichens in China (Wei, 1991) is widely referenced resource used by lichenologists both in China and abroad, documenting 232 genera and 1,766 species. The revised second edition of The Enumeration of Lichenized Fungi in China (Wei, 2020), Including 3,050 species with 419 genera of lichenized fungi and 35 species with 26 genera of lichenicolous fungi. This work is an important reference for scholars studying Chinese lichens both domestically and internationally.

In Northeast China, some of the earliest lichenological studies were conducted by Japanese and Russian scholars. Notable early contributors include Masami Sato, Yasuhiko Asahina, Isao Yoshimura, and the Russian lichenologist Alexander A. Elenkin. The total number of publications by these scholars on this region exceeds one hundred articles. Representative works include Sato's 1937 publication Literature on lichens from China, documenting 117 genera and 770 species of Chinese lichens (Sato, 1937a), and the series Current Research on East Asian Lichens (Parts I and II), describing 124 genera and over 800 species of Chinese lichens (Sato, 1941; 1942). In 1952, Sato and Asahina successively published Licheneses Khinganenses and *An addition to the Sato's Lichenes Kinganenses*, with the former documenting 28 lichen species and the latter 41 species in the Greater Khingan Range (Asahina, 1952; Sato, 1952). Sato's Lichens of the Order Umbilicariaceae (Sato, 1939a) and Asahina's Lichens of Japan (Volumes 1-3) (Asahina, 1950; 1956), also contain early records of lichens from the Northeast China. Additionally, Asahina's works The Raiken's

Soliloquy on Botanical Science and Lichenologische Notizen, as well as publications by Yoshimura and others in The Journal of Japanese Botany and Acta Phytotaxonomica et Geobotanica include collections from the Northeast region.

Before 1949, early Chinese botanist Zhu Yancheng mentioned four types and a single variety of lichens from the Northeast in his study *Note Preliminaire Sur Les Lichens De Chine* (Tschou, 1935). After liberation, Chinese lichen researchers conducted extensive lichen collection in the Northeast region, with Chen Xiling, Luo Guangyu, Zhao Congfu, and others contributing A List of Lichens in N.E. China and Checklist of Northeastern Lichens (II), which reported 195 lichen species and significantly increased the previously recorded 80 species (Chen et al., 1981a; 1981b). These checklists served as a strong reference for lichen research in the Northeast region, and continue to be improved with the addition of publications such as Checklist of Lichens in the Greater and Lesser Khingan Ranges of China. Luo's primary research focused on the Liangshui Nature Reserve and Tahe Forest Area, where he reported on the distribution and ecological characteristics of lichen plants as well as the macrolichens he found in his study area (Luo, 1984; 1986; 1987). Zhao Jiding mentioned lichen species such as *Usnea* and *Parmelia* in the Northeast region (Chao et al., 1975; 1978). In 1984, Hu Yuchen made a significant contribution in the Catalogue of Flora and Flora of Changbai Mountain by reporting a total of 213 lichen species from Changbai Mountain, categorized within 20 families and 43 genera (Hu, 1984). Subsequently, The Plant List of Changbai Mountain, authored by the Changbai Mountain Forest Ecosystem Positioning Station, enumerated 148 species of lichens native to this area (Changbai Mountain Forest Ecosystem Positioning Station, 1982). Towards the conclusion of the 20th century, Zhou Ruichang and colleagues documented an impressive 160 lichen species in Heilongjiang Province (Zhou et al., 1998). In 2013, Zhou Guoli delved into the taxonomy of *Lecanora* lichens in the Northeast region of China through the publication Study on the *Lichen Genus Lecanora from Northeast China* (Zhou, 2013). This work provided an invaluable species identification key, facilitating the identification of *Lecanora* lichens. In 2019, Ren Meirong et al. published a pivotal study Species Diversity of Cetrarioid and Hypogymnioid Lichens (Parmeliaceae, Ascomycota) from the Greater and Lesser Khinggan Mountains in Northeast China. This research illuminated the lichen flora of this region by identifying 31 species and analyzing their ecological conditions (Ren et al., 2019). In the same year, Wei Xinli presented The Checklist of Lichens of the Greater and Lesser Khinggan Ranges of China, focusing on the nomenclature and principal distribution of lichen resources in these mountain ranges, and comprehensively documenting the lichen species therein (Wei, 2019). These scholarly endeavors are foundational in elucidating the composition and distribution of lichens in Northeast China and offer vital insights and trajectories for future research in this domain.

3 Lichen flora information in Japan

Japan is a mountainous island nation where two-thirds of the land is covered by forests. Landscape exhibits significant biodiversity due to its long, narrow shape and a wide range of climates. Lichenology in Japan developed from traditional herbal medicine studies, where lichens, mosses, and algae were initially studied together in the context of natural remedies (Sato, 1934a).The modern study of lichens in Japan was further advanced with the introduction of modern botany from Europe and America. Currently, there are about 1,800 known species of lichens in Japan (Ohmura and Kashiwadani, 2018).

Lichen research in Japan can be divided into several distinct phases based on chronological developments. Initially rooted in traditional herbal medicine studies, lichenology in Japan saw its formative years with the influence of European botanists like Carl Peter Thunberg and Theodor Magnus Fries during the 18th and 19th centuries. The pioneering efforts of Manabu Miyoshi in the late 19th and early 20th centuries laid the groundwork for subsequent research, leading to the emergence of journals like The Journal of Japanese Botany in the early 20th century. The mid-20th century marked a significant period with the contributions of lichenologists Atsushi Yasuda, Yasuhiko Asahina, and Isao Yoshimura, who published seminal works and advanced the understanding of Japanese lichen flora. In the early 21st century, the Japanese Society for Lichenology (JSL) was established, initiating systematic research on lichens in Japan. The findings of these studies were published in its official periodical Lichenology. From the late 20th century to the 21st century, research on Japanese lichens expanded beyond taxonomy to encompass diverse applications in biotechnology, medicine, environmental science, and education, reflecting the growing interest and involvement of researchers in the field.

In the formative years of lichenology, European botanists played a pivotal role in the collection and documentation of Japanese lichens. Notable figures in this endeavor included Swedish botanist Carl Peter Thunberg, Theodor Magnus Fries, Erik Almquist, the lichenologist Johannes Müller Argoviensis, Finnish lichenologist William Nylander, Scottish botanist James M. Crombie, and Finnish lichenologist Edvard August Vainio, among others. Thunberg, in 1784, catalogued 10 species of Japanese lichens, and his landmark publication *Flora Japonica*, released concurrently, documented these species (Thunberg, 1784). In the fifth year of Ansei (1858), Fries first described the novel Japanese lichen species *Stereocaulon japonicum* (Fries, 1858). In 1879, Müller Argoviensis, in *Lichenes Japonici* (Müller, 1879), referenced Almquist's collection of lichens around Mount Fuji, conducted as part of the Swedish Vega expedition. Crombie, in "Additions to the Lichens of the 'Challenger' Expedition," highlighted lichens collected by the Challenger expedition. These European endeavors culminated in a series of studies and publications based on specimens from the Vega and Challenger expeditions (Crombie, 1883; Masters, 1883; Nylander and Crombie, 1883; Nylander, 1890). In 1918, Vainio examined 69 species of Japanese lichen specimens sent by Yasuda (Vainio, 1918), signifying the inception of early European and American lichenological research in Japan (Müller, 1879). British lichenologist Annie Lorrain Smith, in 1921, observed that despite the limited records on Japanese lichenology, the field was incrementally emerging from its nascent stage (Smith, 1921). Manabu Miyoshi (1862-1939) is

celebrated as the pioneer of lichen research in Japan. During his academic career, Dr. Miyoshi authored a 20-part series, elucidating the nomenclature, structure, reproduction, origin, distribution, characteristics, and collection methods of lichens. His work Lichenes. (continuation of the previous title)" constitutes the first exhaustive introduction to lichens in book form in Japan (Miyoshi, 1889; 1890; Makino, 1929). Additionally, Dr. Miyoshi's studies extended to the classification of cryptogamic plants and lower plants, including mosses, liverworts, fungi, and algae, culminating in the publication *Outline of Cryptogamae Japonicae Conibus Illustratae*.

The Botanical Magazine (Shokubutsugaku zasshi) (ISSN: 0006-808X), inaugurated by the Botanical Society of Japan in 1887, stands as a seminal publication, offering a rich repository of literature from the 19th and 20th centuries pertinent to the lichen flora and taxonomy of Japan. This journal embodies the evolution from traditional herbalism to contemporary botanical science. In April 1916, the esteemed botanist Tomitaro Makino established The Journal of Japanese Botany (ISSN: 0022-2062), a publication acclaimed for its substantial influence on the advancement of research in plant taxonomy, herbalism, and an array of related disciplines. Renowned as a premier journal within its field in Japan, it features extensive literature and records concerning lichens in Japan and across East Asia. During the 1930s, the comprehensive Flora Japonica series was unveiled, encompassing ten volumes. Notably, *Flora Japonica* vol.5*, Lichens Peltigerales(1)* and *Flora Japonica* vol.7, *Lichens Lecanorales* authored by Masami Sato, forms a crucial part of this series. Following the release of this series, floristic research on lichens witnessed a significant expansion, extending its scope from Japan to encompass the broader East Asian region.

Throughout the 20th century, Japanese scholars significantly advanced the discipline of lichenology. Prominent figures in this field included Yasuhiko Asahina, Masami Sato, Hiroshi Harada, Isao Yoshimura, Syo Kurokawa, and Hiroyuki Kashitani. In the dawn of the 20th century, lichenological content began to be systematically incorporated into broader botanical works by Japanese botanists. A notable example of this integration is Jinzo Matsumura's seminal work, *Index Plantarum Japonicarum*, published in 1904. The first volume, focusing on cryptogams, meticulously documented an impressive array of 89 genera and 563 species of lichens (Matsumura, 1904). In 1910 (Meiji 43), Kotaro Saita authored an extensive 70-page treatise on lichens, enriched with detailed illustrations, in the publication *Ordinary Flora of Domestic and Foreign Lower Plants* (Saita, 1910). Succeeding the pioneering Miyoshi era in Japanese lichenology, the field transitioned into a new epoch – the Yasuda era. Japanese lichenologist Atsushi Yasuda, mentored by Matsumura and Miyoshi, dedicated his research to the study and collection of lichens across Japan, culminating in the publication of key works in Japanese lichenology (Yasuda, 1921; 1925). Following Yasuda's impactful contributions, Asahina emerged as a formidable figure in Japanese lichenology. In the mid-20th century, he released several seminal works in the field, notably the Illustrated Handbook of Japanese Cryptogamic Plants in 1939, and the *Lichens of Japan (Volumes 1-3)* between 1950 and 1956, thereby significantly enriching the body of knowledge in Japanese lichenology. Asahina also held the esteemed position of chief editor of The Journal of Japanese Botany from 1933 to 1975, where he authored *Lichenologische Notizen* (comprising 254 reports in total) and The Raiken's Soliloquy on Botanical Science (including nearly 300 articles) (Tsumura and Kurokawa, 1975).

Isao Yoshimura emerged as a pivotal figure in the evolution of Japanese lichenology. As a high school student, Yoshimura delved into the study of lichens under the mentorship of Professor Asahina, then regarded as one of Japan's foremost lichen experts. Yoshimura's invaluable research contributions significantly enhanced the understanding of Japanese lichen flora (Yoshimura, 1960; 1962). His seminal work, *Lichen Flora of Japan in Color*, represented the first all-encompassing book on Japanese lichens, documenting approximately 700 species, with 528 species vividly illustrated in color and an additional 155 species described (Yoshimura, 1974). This authoritative reference book, rich in illustrations and covering the majority of Japan's known lichen flora, continues to be an essential resource for students and lichen enthusiasts. Its publication marked a milestone not only in Japan but also in the global field of lichenology, owing to its comprehensive synthesis of species descriptions and visual representations. Prior to the release of this guide, resources on Japanese lichens were markedly scarce. Contemporaneously, lichenologist Sato conducted extensive collections of lichens across Japan and authored numerous articles on novel findings in lichenology, particularly focusing on the Lichen Order Umbilicariaceae and Bryophyta (Tuyama, 1984). In *Lichenological Reports (1-13)*, Sato made significant strides in promoting and advancing lichenology in Japan. *The Miscellanea Bryologica et Lichenologica (1-9)* series, published by the Hattori Botanical Laboratory and co-edited by Sato, is another internationally acclaimed and referenced work (Kurosawa, 1984). Following his publication of *History of Lichenology in Japan* in 1934, Dr. Sato expanded the scope of his research to include East Asia, as evidenced in his 1940 work *East Asiatic Lichens*. Moreover, he continued to probe Japanese lichens, undertaking thorough research on their distribution (Sato, 1956; 1959; 1962). Sato's prolific output on Japanese lichen flora, spanning from 1933 to 1972, includes several noteworthy lichen floras (Sato, 1933; 1934a; 1934b; 1935; 1936a; 1936b; 1937a; 1937b; 1938; 1939a; Sato, 1939b, 1941; 1942; 1943; 1950; 1952; 1954; 1956; 1957; 1959; 1962; 1964; 1968; 1972). Arguably, Sato contributed significant literature of Japanese lichens.

Since the mid 20th century, there has been a notable surge in scholarly output related to the study of Japanese lichen flora. In 1953, Kurokawa comprehensively summarized 142 species of lichens in the Chichibu area. Harada and Kawana (2002) conducted an in-depth study on the lichen flora of Futtsu-shi, Chiba-ken, in central Japan. Shimizu et al. (2004) published *Lichen flora of Mt. Tokachi, Hokkaido, Japan*, a detailed account of the lichen flora of the active volcano Mt. Tokachi in Hokkaido, documenting 159 identified species across 69 genera. Additionally, a plethora of publications has emerged on lichen floras for various regions, providing invaluable references for the study of Japanese lichen flora and enhancing the comprehensiveness of data on lichen diversity in Japan (Kurokawa and Nakanishi, 1971;

Sugiyama, 1979; Ikoma, 1983; Harada and Fukuda, 2001; Shimizu et al., 2004). Japanese lichen checklists are categorically divided into national and regional reference sections. Early on, Sato contributed significant literature on the checklist of Japanese lichens (Sato, 1943; 1964). Ikoma (1916) published a notable lichen checklist for Prov. Inaba. Subsequently, Ikoma released an exhaustive checklist of Japanese lichens, notably providing comprehensive citations for the names used, with detailed information on type specimens for some, transforming it into a valuable reference handbook beyond a mere checklist. Subsequently, Kurokawa also published a checklist of Japanese lichens, considered more authoritative due to its editorial committee comprising 11 lichenologists from four countries. Although two lichen checklists were published in close succession, they are largely complementary in nature (Hawksworth, 2004). In the 21st century, following the establishment of the Japanese Society for Lichenology (JSL), the "Lichen Flora of Japan" Project was launched, significantly advancing the exploration of Japanese lichen taxa. Its core research focused on the taxonomy of Japanese lichenized fungi, contributing multiple lichen inventories. The JSL first compiled a national checklist titled *Checklist of Lichens and Lichen-Allies of Japan* by Harada, documenting 317 genera and 1,602 species (Harada et al., 2004). This was followed by the publication of *Taxonomic Arrangement of Lichens and Lichen-Allies of Japan*, which presented lists encompassing 1,906 lichen-forming fungi and related fungal groups in Japan. The compilation includes 1,801 accepted taxa, comprising 389 genera, 1,764 species, 10 subspecies, 49 varieties, and 11 forms (Yoshimura et al., 2006). Subsequently, multiple scholars conducted genus-level revisions and published lichen inventories for all 47 prefectures of Japan between 2006 and 2013. Major regional lichen checklists include *Lichens on Mt. Koya*, *Lichen Catalogue of the Northern Kuril Islands*, *Lichen Catalogue of Ibaraki Prefecture*, *Lichens of Mt. Tsukuba*, *Lichen of Mt. Kaba*, *Lichens of Shodoshima*, *Lichen Catalogue of Kyoto Prefecture*, and *Lichens of Wakayama Prefecture*, among others (Yamamoto, 2006; 2007; Harada, 2008; Yamamoto, 2008). These were supplemented by specialized inventories for unique habitats such as marine/maritime and freshwater environments. Additionally, numerous papers reporting new species and rare lichens in Japan have been published. This comprehensive series of studies has clarified the distribution patterns of Japanese lichens and greatly propelled related research advancements (Harada, 2020).

The most recent lichen checklist of Japan is the Checklist of Lichens and Allied Fungi of Japan, published by Ohmura and Kashiwadani in 2018 on behalf of the Lichenological Society of Japan. Japanese Society for Lichenology and the Lichenological Society of Japan are main resources for lichenologists, and The Japanese Society for Lichenology publish the Society publication Lichenology and Lichenological Society of Japan publish the bulletin Lichen, which contain additional valuable research references. Current research on Japanese lichens has expanded from its initial focus on taxonomy and chemical components to applications in biotechnology, medicine, environmental science, dyes, pharmaceuticals, and education. The number of researchers in lichenology increasing, particularly in biotechnology, where Japan has become a world leader (Yoshihito et al., 2012; Nakajima et al., 2013; Ohmura et al., 2014; Nakajima et al., 2015; Dohi et al., 2021).

4 Lichen flora information on the Korean Peninsula

The Korean Peninsula, situated in the northeastern part of the Asian continent, is predominantly mountainous, with mountains and plateaus covering two-thirds of its area (Dong, 2005). This region boasts rich biodiversity, including over 1100 lichen taxa (National Institute of Biological Resources, 2019).

Lichen research on the Korean Peninsula has evolved through distinct phases over time. Initially, European scholars and Japanese botanists contributed significantly to understanding lichen distribution and taxonomy on the peninsula, laying the groundwork for subsequent research. During Japan's occupation of Korea, extensive botanical research, including lichen studies, was conducted. However, lichenological research in Korea progressed independently after the Korean War, with scholars like Ri in North Korea, Kim and Park in South Korea making notable contributions. In North Korea, Ri published the first checklists of North Korean lichens and contributed to international publications, while in South Korea, Kim and Park pioneered comprehensive inventories of Korean lichens. In the late 20th and early 21st centuries, efforts to document and catalog Korean lichens intensified, leading to the establishment of the Korean Lichen Research Institute and the publication of comprehensive lichen catalogs and encyclopedias. These resources, coupled with international collaborations and advancements in biodiversity conservation, have enriched our understanding of lichen diversity on the Korean Peninsula.

The first report on Korean lichens was made by Hue in 1915 (Hue, 1915). Subsequent studies on lichens in the Korean Peninsula were primarily carried out and published by European scholars and Japanese botanists, such as Hue, Aptroot, Cardot, Choe, Nakai, Hong, Hattori, Noguchi, Okamura, Osada, Sato, Asahina, and Inoue (Hue, 1909; 1910; 1912; Asahina, 1934). However, most of these articles focused on studying lichen distribution in specific regions of the Korean Peninsula and describing lichen taxa (Sato, 1939b; Hong, 1962; Choe and Yamada, 1997; Song and Yamada, 2001). Overall, lichen research on the Korean Peninsula has primarily focused on floristic surveys and species diversity.

Japan occupied the Korean Peninsula for nearly half a century, considering it a crucial reservoir of biodiversity. Consequently, Japanese botanists conducted extensive research on the peninsula (Wang et al., 2020). In 1917, Takenoshin Nakai published The Flora of Sorak-san in Korea, documenting 14 lichen species. This was followed by the publications The Flora of Baekdu Mountain and The Flora of Geumgang Mountain in 1918. The former offered detailed descriptions of fruticose lichens, while the latter listed eight species of lichens identified by Miyoshi (Sato, 1939b). In 1933, Kaname Takenaka published Alpine Plant Collection in the Crowned Peaks, documenting plant collections from the Showa era's 7th year, including a catalog of seven lichen species. Subsequently, in 1934, Joichi Ueda documented Common Lichens Found in Baekdu Mountain in the Journal of the Korean Museum, detailing 22 lichen species across 7 families from his collection (Sato, 1939b). Furthering this research, in 1935, Tohru Miyoshi published Alpine and Medicinal Plants in the Mountainous Regions of South Hamgyong in the Journal of the Korean Museum, listing

20 lichen species across 5 families identified by Professor Taihiko Asahina. Asahina and Sato contributed numerous articles to the Botanical Research Journal discussing the lichens of the Korean Peninsula (Asahina, 1934; Sato, 1934b; Asahina, 1939). In 1939, Tsukini Sato published Data on lichens originating in Korea in the Botanical Research Journal, providing an overview of lichen types in the Korean Peninsula along with relevant literature.

In the aftermath of the Korean War, lichenological research in Korea progressed independently within both North Korea and South Korea. In North Korea, Ri Jong Dzae emerged as a central figure in the study of Korean lichens and was recognized as the sole lichenologist in the country at that time (Szerdahelyi and Lőkös, 1992). In 1983, he authored the inaugural checklist of North Korean lichens, encompassing a total of 247 species (Ri, 1983). Subsequently, in 1988, Ri released a second checklist; however, both compilations were observed to be lacking in crustose lichens (Ri and Hyun, 1988). Additionally, Ri presented an exhaustive report titled Spore Plants of Korea. 7. Lichens, delving into the distribution of lichens in Korea. Contrastingly, the academic cataloging of Korean lichen flora was predominantly conducted by Eastern European geographers, rather than North Korean lichenologists (Ri, 1988). Significantly, former East German lichenologist Huneck provided critical insights into North Korean lichens and those from Mount Diamond through his reports to the international academic community in 1989 and 1994. These publications remained the principal source of information on North Korean lichens accessible to South Korean scholars until the late 1990s (Huneck et al., 1989). This research, covering lichens across both North and South Korea, holds significant value for South Korean mycologists and lichenologists. When Hungarian lichenologist Lökös visit to North Korea, he received a manuscript detailing lichen species distributed in Myohyangsan from North Korea lichenologist. This manuscript is considered one of the earliest local lichen catalogs of North Korea, although a significant portion of the classification system used differed greatly from the current system. Additionally, North Korean lichen literature primarily utilized Japanese documents and taxonomic indices as it was compiled (Asahina, 1934; Song and Yamada, 2001). In 1990, Hawksworth and Ahti documented an extensive array of 248 lichen species in North Korea (Hawksworth and Ahti, 1990). Subsequently, during their second botanical expedition to North Korea, Szerdahelyi and Lőkös from the Hungarian Natural History Museum undertook field research in three principal locations: Pyongyang, Mount Diamond, and Mount Baekdu. This endeavor resulted in the collection of 380 lichen specimens (Szerdahelyi and Lőkös, 1992). In 2009, H. S. Jeon and colleagues published a pivotal report, *Report on the Lichen List of North Korea*, detailing 179 species of lichens in North Korea, encompassing 26 families and 57 genera, and highlighting 17 species newly reported in the region. This catalog also introduced 29 novel lichen species to the Korean Peninsula, establishing itself as a vital resource for the study of lichens in the area (Jeon et al., 2009).

From a South Korean standpoint, the early foray into lichenological studies saw contributions from scholars such as Kim, Park, Moon. Kim was prolific in publishing numerous scholarly articles on lichen research (Kim, 1965; 1979; 1980). Notably, Kim's 1981 work Floral Studies on the Lichens in Korea marked a significant milestone as the first Korean lichen inventory to include a key, documenting 246 species across 52 genera. Following this, Park released Checklist of Korean Lichens, enumerating 177 species across 31 genera in South Korea. In 1990, Park pioneered the first international journal article on the extensive lichen flora of Korea, offering comprehensive descriptions of each species. The report catalogued 189 species across 17 families and 46 genera, with most specimens originally housed in South Korea but tragically destroyed in a fire. However, some duplicate specimens remain in herbaria in the USA and Europe (Park, 1990). In 1996, the Korean Nature Conservation Association listed a significant 496 species of lichens in The Inventory of Korean Species. Subsequent research endeavors continued to explore the lichen flora of South Korea (Ka et al., 1997; Moon, 1999; Kashiwadani et al., 2002; Moon and Kim, 2002). The Korean Lichen Research Institute (KoLRI) was established in 2002, distinguishing itself as the sole specialized institution in South Korea dedicated to lichen research. Since then, active lichen research has been formally conducted centering on the National Institute of Biological Resources, the Korean Lichen Research Center at Sunchon National University, and the Korea National Arboretum. Post Park's study in 1990, comprehensive nationwide lichen surveys were not conducted until 2003, when the South Korean government initiated a series of biodiversity conservation programs. As part of these initiatives, a long-term project on the lichen flora of South Korea was launched. Hur and colleagues provided an insightful overview of the current status of lichenology in South Korea and reported the distribution of 95 macrolichen groups in the country (Hur et al., 2004). In 2005, Hur and others published a catalog of Korean lichens, listing 510 species in 113 genera. The 2013 publication Lichen-forming and Lichenicolous Fungi of Korea recorded a comprehensive 788 taxonomic units across 180 genera of lichens (Moon, 2013). In 2015, the Korean Botanic Garden unveiled South Korea's inaugural lichen encyclopedia, a culmination of the first tranche of results from extensive lichen surveys and research conducted over decades. This authoritative work featured 199 species of lichens and boasted approximately 500 photographs. Subsequently, in 2016 and 2018, South Korea released Flora of Macrolichens in Korea 1 and Flora of Macrolichens in Korea 2, respectively. These volumes examined specimens amassed over the past decade, yielding verified specimens of 287 taxonomic units across 59 genera and 292 taxonomic units across 59 genera, respectively. Significantly, these publications included bilingual taxonomic descriptions (in English and Korean), national distribution maps, distribution altitudes, ecological photos, and microphotographs for each genus and species. These comprehensive resources serve as indispensable references for Korean lichen research, providing exhaustive information on common Korean lichens (Hur et al., 2016, 2017).

The Great Dictionary of Korean Plants is the only research work to date that compiles the distribution and status of Korean Peninsula plants, including lichens, amidst the fact that studies are usually carried out separately due to political tensions between North Korea and South Korea. This work uses major global plant registration systems like the Soviet Union's plant register and the

Engler system, and includes a lichen index (North Korean Academy of Agricultural Sciences, 2001). The 2019 publication National Species List of Korea. I. Plants, Fungi, Algae, Prokaryotes documents 1,133 native lichen species of the Korean Peninsula. For the lichen catalog of the Korean Peninsula, one can access the regularly updated national species database through the Korean Peninsula Biodiversity website (https://species.nibr.go.kr/index.do) and the National Biodiversity Information Sharing System (http://kbr.go.kr), which currently includes 1,189 species of lichens.

5 Lichen flora information in the Russian Far East

The Russian Far East refers to the vast eastern territories of Russia, which is defined in accordance with the World Geographical Scheme for Recording Plant Distributions, and adopted for use with lichen flora. The region shares land borders with China and North Korea and maritime borders with Japan and the United States, thereby constituting an integral part of Northeast Asia. This expansive area encompasses nine federal subjects, including Khabarovsk Krai, Primorsky Krai, Amur Oblast, the Jewish Autonomous Oblast, Magadan Oblast, Sakhalin Oblast, Kamchatka Krai, and the Chukotka Autonomous Okrug. The Russian Far East spans multiple climatic zones, ranging from Arctic tundra in the north to temperate monsoon climates in the south, and supports exceptionally high levels of biological diversity.

Lichen research in the Russian Far East has a long history, dating back to the mid-18th century, when German naturalists in the service of the Russian Academy of Sciences were involved in the earliest lichen collections and studies. From the 18th to the 19th century, lichen-related research in the Far East was largely based on specimen collections obtained during exploratory expeditions and was typically presented as appendices to botanical or natural history works. These specimens were subsequently examined, organized, and published by European and Russian taxonomists within regional floristic and systematic studies. From the beginning of the 20th century, lichen research and surveys in the Russian Far East increasingly came to be led by Russian scholars, and studies of Far Eastern lichens gradually shifted from a peripheral endeavor to an integral component of nationwide systematic research. Comprehensive regional surveys established datasets that could be accumulated and compared over the long term. From the late 20th century into the 21st century, lichenological research in the Russian Far East expanded rapidly, with a growing number of researchers and an increasingly broad geographical scope encompassing multiple regions of the Far East.

The Second Kamchatka (Great Northern) Expedition in the mid-18th century marked the beginning of exploration and botanical collection in the Russian Far East. The German naturalist Johann Georg Gmelin (1709-1755), as one of the leaders of the Academic Detachment, participated in the expedition and conducted research in Eastern Siberia. His student, Stepan Petrovich Krasheninnikov (1711-1755), was dispatched by Gmelin, together with Georg Wilhelm Steller (1709-1746), to investigate the Kamchatka region (Egerton, 2008). After a decade of observation and study, the four-volume Flora Sibirica was published, the preface of the fourth volume explicitly noting the rich lichen flora of the region and reporting numerous collected specimens (Gmelin, 1769). Entering the 19th century, Russian-organized expeditions continued to make significant contributions to the accumulation of lichen specimens. For instance, Ferdinand von Wrangel collected data on the natural resources of Chukotka and the Arctic Ocean (Wilson and Fiske, 1889), while Alexander von Middendorff conducted expeditions across Siberia and the Far East, covering areas such as the Taimyr Peninsula, the coast of the Sea of Okhotsk, and the upper reaches of the Amur River (Tammiksaar and Stone, 2007). These expeditions further enriched the lichen collections from the Russian Far East. William Nylander (1822-1899), a prominent 19th-century lichenologist, described and identified a large number of lichen specimens from around the world. His taxonomic work exerted a influence on the early understanding of Russian lichens. In 1888, he published *Enumeratio Lichenum Freti Behringii* (Nylander, 1888), in which he identified and analyzed lichens collected by Almquist during 1878–1879 in the region surrounding the Bering Strait, including parts of Chukotka and Kamchatka in the Russian Far East. Edvard August Vainio (1817-1885) also examined lichen collections from the Arctic coast, including parts of the northern Pacific coast in Chukotka, Russian Far East, and described approximately 100 species as new to science (Väre, 2017), publishing the specialized study *Lichenes in viciniis stationis hibernae expeditionis Vegae prope pagum Pitlekai in Sibiria septentrionali a Dre Almquist collecti* (Vainio, 1909). Overall, during this period, lichen studies in the Russian Far East were primarily focused on specimen collection, with only sporadic literature records.

In the late 19th — first half of the 20th century., lichen research in the Russian Far East entered a new phase of development, largely owing to the contributions of Alexander Alexandrovich Elenkin (1873–1942), who is widely regarded as the founder of the Russian school of lichenology (Andreev and Potemkin, 2023). The publication *Lichens Florae Rossiae et Regionum Confinium Orientalium* represents a synthesis of the earliest studies on the lichen flora of the Far East (Elenkin, 1901). In addition to producing fundamental scientific works—many of which remain relevant to this day—Elenkin also trained a cohort of outstanding students who continued and further advanced the development of Russian lichenology (Davydov, 2023). Among the students of Elenkin, Vsevolod Pavlovich Savich (1885–1972) played a direct and pivotal role in the early study of cryptogamic plants (including lichens and bryophytes) in the Russian Far East. In 1908–1909, the expedition led by Komarov to Kamchatka in which Savich participated as a botanist specializing in cryptogams. During this expedition, he assembled a large and valuable collection of lichens, algae (both freshwater and marine), fungi, and mosses (Avetisov, 2017). This Far Eastern expedition was decisive for Savich's formation as a scientist and provided a material foundation for the study of cryptogamic botany in the Russian Far East. Over the course of his scientific career, Savich published approximately 180 research papers. Although his work was not exclusively focused on

the Far East, his publications, together with those of other specialists, laid a solid foundation for subsequent floristic, systematic, morphological, ecological, and biochemical studies of lower plants in the region, including lichens, bryophytes, fungi, and algae (Golubkova, 2003). It is also noteworthy that, beginning in 1922, under the editorship of Elenkin, the serial publication Botanical Materials of the Institute of Cryptogamic Plants of the Main Botanical Garden of the Russian Soviet Federative Socialist Republic was launched. This publication was later continued under the title *Novosti sistematiki nizshikh rastenii* and has been published continuously to the present day, serving as one of the most important outlets for taxonomic and floristic studies of lichens in the Russian Far East.

By the mid-20th century, the Russian Far East had become a focal point for frontier scientific research and resource surveys. The Academy of Sciences of the USSR established the Far Eastern Branch of the Academy of Sciences, marking a significant milestone in the history of lichen research in the Russian Far East. The establishment of this institution created a research network covering the entire Far Eastern Federal District, providing stable institutional and personnel support for lichenological studies and integrating the region, for the first time, into Russia's systematic framework for biogeographical and ecological research. This integration is reflected in multi-volume works such as *Handbook of the Lichens of the U.S.S.R.* (1971, 1974, 1975, 1977, 1978) and *Handbook of the Lichens of Russia* (1996, 1998, 2003, 2004, 2008). At the same time, monographs treating the Far East as an integrated research unit were published successively, significantly enhancing the scientific community's overall understanding of lichen diversity in the region. Among these contributions, perhaps the most influential is A Conspectus of Lichen Flora of the South of the Russian Far East by Svetlana Ivanovna Chabanenko (1954–2018). This work represented the first comprehensive synthesis of all available literature and her own observations on the lichen flora of the southern Russian Far East, covering primarily Sakhalin Island, the Kuril Islands, the Commander Islands, and adjacent continental areas including Primorsky Krai and Amur Oblast (Chabanenko, 2002). The publication provided a systematic compilation and review of species composition, taxonomy, ecological distribution, and biogeographical characteristics of the region's lichens. It has frequently served as a key reference in subsequent regional studies.

From the 20th century to the early 21st century, lichen research in the Russian Far East entered a phase of rapid development, with systematic surveys of lichen resources being successively carried out across the various regions of the Far East. Lichenological studies in the Primorsky Krai (Maritime Territory) of Russia commenced in the 1920s. By 1969, the known lichen diversity of Primorsky Krai had increased to 156 species (Skirina and Moiseevskaya, 2004). After 1969, lichen research in Primorsky Krai was characterized by systematic and planned investigations, with an emphasis on the lichen flora of nature reserves. As a pioneer of these systematic studies, Knyazheva conducted the first comprehensive analysis of the lichen flora of southern Primorsky Krai and compiled a species list organized by substrate type (Knyazheva, 1973). In the 1980s, Chabanenko further investigated the lichen flora of southeastern Primorsky Krai, including a study on Putyatin Island (Chabanenko, 1986). From 1975 onward, Skirina carried out surveys in the northern part of the region and conducted a series of studies on nature reserves, producing detailed species lists for the Sikhote-Alin Nature Reserve, Bastak Nature Reserve in the Jewish Autonomous Region, and Kedrovaya Pad Nature Reserve in Primorsky Krai, documenting species distributions, vegetation types, and substrate preferences (Skirina, 2015b; 2015a; 2017). Significant contributions were also made by Mikulin Rodnikova, and Galanina, while lichenologists from Estonia, Sweden, and Japan participated in related research during the same period (Skirina and Moiseevskaya, 2004). The main contributor to systematic lichenological research in the Chukotka region was Makarova. She reported new species records and conducted taxonomic studies on genera such as *Pertusaria* and *Ochrolechia* (Makarova, 1973; 1975; 1976; 1977; 1979b). Makarova also carried out ecological and community-level analyses, examining lichen floras in the lower reaches of the Amguema River as well as in mountainous and lowland areas (Makarova, 1979a; 1987; Makarova and Katenin, 1987). In addition, other researchers, including Dobrysch, Dombrovskaya, and Katenin, contributed significantly to the lichenological studies of the region (Dombrovskaya and Makarova, 1982; Makarova and Katenin, 1983; 1987; Dobrysch, 1995; Dobrysch and Makarova, 1998). In the Chukotka region, lichens are often studied as part of broader research on Arctic lichens and are regularly documented in related investigations. In 1996, Andreev and colleagues published *the Checklist of Lichens and Lichenicolous >Fungi of the Russian Arctic*, documenting 1078 species of lichens and lichenicolous fungi based on specimens collected in the Russian Arctic and related literature (Andreev et al., 1996). The 2010 publication *Panarctic* Checklist of Lichens and Lichenicolous *Fungi* updated and supplemented the previous checklist (Kristinsson et al., 2010). According to this checklist, the number of lichen species recorded for the Beringian Chukotka part reached 675, while the total number of species for the Continental Chukotka part was 757 (Chesnokov et al., 2025). In the Magadan region, significant contributions to lichen research were made by Zhurbenko, Zheludeva, Andreyev, and Lokinskaya (Lokinskaya, 1966; Andreev, 1978; Zhurbenko and Zheludeva, 2015). However, up until the early 21st century, research in the Magadan region remained incomplete (Zhurbenko, 2003; Kotlov, 2004; Zheludeva, 2017; Galanina et al., 2021; Suleimen et al., 2022). With regard to the Kamchatka Peninsula, Trass published a study on the lichens of the Kamchatka Peninsula in 1963. Subsequent reports highlighted specific areas, such as Khodosovtsev and others' 2004 report on 22 species of the lichen genus *Caloplaca* in the Kamchatka Peninsula (Khodosovtsev et al., 2004). Additionally, reports by Zhurbenko and colleagues documented 48 lichen species, in the Kamchatka Peninsula, detailing their distribution (Zhurbenko et al., 2012). Russian lichenologists Himelbrant and Stepanchikova, along with their colleagues, have engaged in thorough research on the lichens of the Kamchatka Peninsula. In 2011, they explored the lichen flora of the Kamchatian fir grove within the Kronotsky Nature Reserve and assembled a comprehensive checklist for the reserve (Himelbrant and Stepanchikova, 2011). Subsequently, in 2019,

Himelbrant embarked on the pioneering lichen inventory of northern Kamchatka Peninsula, cataloging an impressive 315 lichen species (Himelbrant et al., 2019). In 2021, Himelbrant and associates conducted a novel survey in Koryakia, with a primary focus on the lichens at Cape Goven on the Bering Sea coast (Northern Kamchatka, Russia), identifying a total of 394 taxonomic units in the area (Himelbrant et al., 2021). Research has been notably concentrated on the lichens of the Kuril Islands, as detailed in publications such as Notes on the Lichen Flora of Tisima or the Kuriles, To the Lichen Flora of Kunashir (Kuril) Island, and Lichens of the Kuril Reserve (Kunashir Island) (Sato, 1936b; Bredkina et al., 1992; Chabanenko, 1999). Exploratory expeditions and surveys in the Sakhalin region, conducted by Chesnokov, Konoreva, and Skirina, have been instrumental in the study of lichens on Iturup Island (part of Russia's Far Eastern Sakhalin Oblast) and the swamps of Sakhalin Island. These efforts have elucidated the regional lichen species composition (Chesnokov and Konoreva, 2021; Skirina et al., 2021). The discrepancies in research coverage highlight gaps, most notably in the Khabarovsk and Amur regions, which lack adequate attention from lichenologists. To date, a comprehensive study encompassing the full spectrum of lichens in the Russian Far East has yet to materialize.

In the new millennium, Urbanavichus published A Checklist of the Lichen Flora of Russia, representing the first systematic compilation of all known lichens of Russia, encompassing a total of 2,925 species (Urbanavichus, 2010). Lichenologists at the Komarov Botanical Institute in St. Petersburg have concentrated their efforts on *Lichen Flora of Russia* project, which has been published in four volumes (2014, 2017, 2022, 2023). Currently, researchers of lichens in the Russian Far East focus particularly on lichen taxonomy and regional floristic studies. The scope and frequency of field surveys continue to expand, and researchers are actively involved in investigations of protected areas, as well as in the preparation of Red Data Books, comprehensive floristic checklists, and regional species inventories.

6 Lichen flora information in Mongolia

Mongolia, situated between China and Russia in Central Asia, stands as the world's second-largest landlocked country. Presently, researchers have identified over 1000 lichen species within Mongolia (Ochirbat et al., 2020).

Exploration into Mongolian lichens commenced in the early 20th century, with minimal studies conducted before this era (Golubkova, 1981). The pioneering research on Mongolian lichens was initiated by Russian lichenologists. European and Mongolian researchers later contributed to the exploration and cataloging of Mongolian lichens. Notable publications include Vězda's pioneering work in 1965 and Schubert and Klement's systematic catalog in 1971. Collaborations between Mongolian and international scientists, such as Golubkova and Huneck, significantly advanced the field. Subsequent comprehensive catalogs by Cogt and Biazrov established valuable resources for Mongolian lichen research. In the 21st century, institutions like the Mongolian Academy of Sciences and the Russian Academy of Sciences continue to drive research, focusing on diversity, phytogeography, and the role of lichens in soil crust formation.

Elenkin's early 20th-century work, Kratkiy Predvaritelny Otchet o Sporovykh, Sobrannykh v Sayanskikh Gorakh Letom 1902 g., contains earliest data on Mongolian lichens and may be among the initial publications in this field (Elenkin, 1902). Subsequently, lichenologists from the Czech Republic, Germany, Finland, and Mongolia itself actively engaged in collecting and studying Mongolian lichens. Contributors such as Vězda, Klement, Schubert, Tsogt, Golubkova, Biazrov, Ahti, Olech, Cogt, and Javkhlan, among others, conducted research in this domain. However, most of these studies concentrated on local lichen species within Mongolia, with few encompassing comprehensive analyses of lichens across the entire region. Overall, the initial exploration of Mongolian lichens owes much to the pivotal role played by European lichenologists.

During the 1970s, Mongolian lichen research witnessed a focused and productive phase, marked by significant publications. Notable works included Antonín Vězda's *Flechten aus der NW-Mongolei* in 1965, a pioneering contribution. Rudolf Schubert and Oskar Klement's 1971 publication *Beitrag zur Flechtenflora der Mongolischen Volksrepublik* stands out as the first systematic catalog of Mongolian lichens, documenting 328 species and offering an initial overview of Mongolia's lichen flora (Schubert and Klement, 1971). Golubkova published A Contribution to the Knowledge of the Lichenoflora of Mongolian People's Republic two years later, detailing 65 species of Mongolian lichens (Golubkova, 1973). Collaborating with Mongolian lichenologist Cogt, she further contributed to lichen research with *De Lichenibus Partis Republicae Popularis Mongoliae Dolina Ozer Dictae Notula* (Golubkova and Cogt, 1974). Notably, Golubkova, as a researcher at the Academy of Sciences of the USSR, participated in the Soviet-Mongolian Biological Expedition, collecting numerous lichen specimens and co-publishing related articles with Mongolian lichenologists (Golubkova and Tsogt, 1974). Additionally, based on her extensive research, she authored Conspectus Lichen Flora of MNR and Analyze of Lichen Flora in Mongolia, providing an overview of Mongolian lichen flora characteristics and distribution patterns.

During this period, Mongolia engaged in a collaborative biological expedition with Germany, culminating in the publication *Flechten aus der Mongolischen Volksrepublik Ergebnisse der Mongolisch-Deutschen Biologischen Expedition seit 1962 Nr. 7*. This work meticulously documents lichen materials collected during the 1964 Mongolian-German biological expedition in the central and western regions of the Mongolian People's Republic (Golubkova, 1981). Additionally, Cogt stands out as a key figure in Mongolian lichenology. He comprehensively introduced the history of lichenological research in Mongolia, delineated phytogeographic regions, and identified 212 species of lichens distributed across 25 families and 55 genera (Cogt, 1979). Moreover, he conducted a detailed study of the lichens of the Prikhubsugol region in Mongolia, substantially enriching the data on Mongolian lichens (Cogt, 1976). Beyond Cogt, other scholars have made significant contributions to the study of the lichen flora of Mongolia. For example, Byazrov conducted comprehensive research on the lichens of the Khangay region in Mongolia (Byazrov, 1983; 1986; 1989). Sedelnikova explored the lichen flora of northern Mongolia (Sedelnikova, 1985). Åšliwa and Wilk undertook research on

Mongolian lichens collected from Lake Khubsugul National Park (Wilk and Åšliwa, 2006; Wilk, 2007). Collectively, these studies significantly enhance the understanding of the diversity and distribution of lichens in Mongolia, underscore the nation's rich lichenological heritage, and emphasize the pivotal role of international collaboration in this scientific domain. Ahti, a distinguished Finnish botanist and lichenologist renowned for expertise in the Cladoniaceae family of lichens, published extensively, including specialized research on Cladoniaceae lichens in Mongolia. His 1976 work The Lichen Genus Cladonia in Mongolia documented 32 species of Cladoniaceae lichens from Mongolia, based on collections and field notes from 1970 and 1972. German lichenologist Siegfried Huneck made substantial contributions to the study of Mongolian lichens and phytochemistry. He conducted in-depth research on the distribution and chemical properties of Mongolian lichens, drawing upon data from Mongolian-German biological expeditions since 1962 (Huneck et al., 1987, 1992). Over a distinguished career spanning from 1958 to 2010, Huneck authored over 40 scientific publications, specifically addressing Mongolian phytochemistry and lichens. In collaboration with Mongolian colleagues like Khaidav, Cogt, and other international experts, his work significantly expanded the scientific understanding of Mongolian lichens (Grolle et al., 1983; Huneck et al., 1984; Huneck and Knapp, 1988; Huneck et al., 1988). In 2006, Hilbig provided a comprehensive review of Germany's contributions to research in Mongolia, highlighting the early endeavors of East German botanists. This review also encompassed studies on the lichen flora, rendering it a pivotal resource for grasping the historical context of lichenological research in Mongolia (Hilbig, 2006). Collectively, these efforts have been instrumental in deepening the understanding of the diversity and chemical properties of lichens in Mongolia, underscore the invaluable role of international collaboration in propelling the field of lichenology forward. More than two decades after the initial publication Mongolia's first lichen catalog, Cogt's *Die Flechten der Mongolei* documented 912 Mongolian lichen species, providing details on their ecology and distribution. Subsequently, Biazrov. released four editions of the Mongolian lichen catalog, beginning in 2003. The 2013 edition, titled Composition of Lichen Species of Mongolia and Its Distribution on Floristic Districts of the Country expanded the list to 1069 species, establishing itself as a pivotal resource for Mongolian lichen research in the 21st century (Byazrov, 2013).

In the 21st century, key institutions driving research on Mongolian lichen diversity include the Institute of Botany at the Mongolian Academy of Sciences, the Komarov Botanical Institute at the Russian Academy of Sciences, and the W. Szafer Institute of Botany at the Polish Academy of Sciences. Renowned researchers such as Enkhtuya, Javkhlan, Zhurbenko, Wilk, Palka, and Śliwa have contributed significantly to exploring Mongolian lichen diversity and phytogeography, producing numerous publications in the field. Beyond the investigation of Mongolian lichen diversity, some lichenologists have ventured into studying lichens' relationship with soil crusts. For instance, Biazrov's 2015 publication Contribution of Lichens in the Formation of Biological Soil Crusts in the Steppes of the Khangai Upland (Mongolia) and Kemmling's 2012 article Bacterial Diversity in Biological Soil Crusts from Extrazonal Mountain Dry Steppes in Northern Mongolia delve into this specific area of research.

7 Discussion

Lichen research in Northeast Asia presents unique characteristics in each country's approach. China has a long history of extensive research and abundant lichen resources. Meanwhile, Japan has played a pivotal role in advancing modern lichenology. In contrast, Korean research, which commenced in the 1990s, primarily focuses on phytogeographical surveys of lichens. However, despite this effort, most findings have not garnered international recognition, many specimens are held abroad. This signifies the pressing need for increased international collaboration in Korean lichen studies. Lichen research in the Russian Far East currently lacks comprehensive and systematic studies, primarily centering on specific protected areas or taxonomic groups. Mongolia's exploration of lichens is still at an early stage. Nevertheless, studies within the country are vital for comprehending the ecology and distribution of lichens in inland regions. North Korea's research remains relatively isolated, with its research findings and distribution data rarely made publicly available. These facets underscore the diverse landscape of lichen research in Northeast Asia and highlight the challenges faced by different countries, such as the imperative for international cooperation and the role of technological advancements.

With the rapid development of biodiversity information databases, most countries in Northeast Asia have established relevant databases to advance lichen research. For instance, China provides online information on known animals, plants, fungi, and microorganisms through *the Species 2000 China Node* (http://www.sp2000.org.cn/), adhering to *the Species 2000* standard data format, and offers free services to users worldwide. Japan has established The Database for DNA-barcoding of the Japanese Lichens (https://lichenology-jp.org/dna/index.php) to assist in lichen identification and classification. Russia launched t*he Plantarium. Plants and lichens of Russia and neighboring countries: open online galleries and plant identification guide* (https://www.plantarium.ru/). South Korea introduced the National Standard Lichen Catalog on its National Species Information System. Additionally, the National Biodiversity Information Sharing System (http://kbr.go.kr) grants access to the regularly updated database of the National Species Catalog of South Korea. To explore information about lichens on the Korean Peninsula, the website (https://species.nibr.go.kr/index.do) is a valuable resource. According to our incomplete statistics, there are more than 450 monographs and research papers specifically devoted to lichen taxa in different regions of Northeast Asia. However, with the enrichment of data sources, the shortcomings and deficiencies in independent research conducted by various countries are becoming increasingly apparent. When further analyzing and integrating taxonomic changes and heterogeneous data from multiple sources, the different classification systems and naming conventions used by different countries result in a large number of synonyms for the same taxon, leading to distorted counts of taxa in certain regions. Currently, such data continue to appear in various datasets, particularly in online databases with insufficient review processes. Therefore, to obtain comprehensive, accurate, and reliable data on Northeast Asian lichens, it is necessary to collect more sufficient data in subsequent work, unify taxonomic systems, eliminate synonyms, and emphasize rigorous data upload reviews.

8 Conclusions and future directions

In Northeast Asia, lichen research has a rich historical background and encompasses diverse research trajectories in each country. Individual nations have distinct focuses and achievements in categorizing, understanding ecological behaviors, and mapping the geographic distribution of lichens. However, given the relatively independent nature of research efforts across different countries, it is imperative to accelerate the establishment of regional cooperation and develop permanent cooperative mechanisms. We should also advocate for the participation of more institutions, teams, and individuals to join us in collectively studying organisms within the Northeast Asian region. This collaboration aims to resolve taxonomic and distributional issues, thereby better promoting biodiversity conservation in Northeast Asia. The following recommendations are proposed: (1) Continue prioritizing field surveys, expanding their geographical scope and increasing their frequency.(2) Break down barriers between nations and establish joint scientific expeditions to investigate unique transboundary geographical units, such as the Mongolian Plateau, and compile regional species inventories.(3) Establish a real-time updating regional biodiversity database. This database should encompass critical information such as habitats, distributions, and voucher specimens, and should regularly integrate and clean data from diverse sources. (4) Build on the resources of institutions like the Northeast Asia Biodiversity Research Center and the Japanese Society for Lichenology (JSL) by creating more cross-regional centers, such as the Sino-Russia Joint Center for Biodiversity Research. This approach will continuously strengthen regional cooperation, develop more local scholars, and promote progress in lichen research and biodiversity conservation across Northeast Asia.

Author contributions

XL: Writing – review & editing, Writing – original draft. YL: Writing – original draft. XD: Formal analysis, Writing – review & editing. LZ: Formal analysis, Writing – review & editing. SW: Formal analysis, Writing – review & editing. HW: Conceptualization, Supervision, Writing – review & editing. CY: Conceptualization, Supervision, Writing – review & editing. KM: Project administration, Writing – review & editing.

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