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Concise review of the brown algal genus *Padina* (Dictyotaceae): knowledge in biodiversity, biogeography, potential and scope future research for Vietnam

Linh Manh Nguyen[1,2], Shingo Akita[3], Luong Van Cao[1], Anh Nguyen Thi Mai[1], Quang Van Pham[1], Hung Manh Vu[1], The Duc Nguyen[1], Vy Xuan Nguyen[2,4], Quan Van Nguyen[1,2,*], Christophe Vieira[2,5,**]

[1]*Institute of Marine Environment and Resources, VAST, Vietnam*
[2]*Graduate University of Science and Technology, VAST, Vietnam*
[3]*Faculty of Fisheries, Hokkaido University, Hakodate 0418611, Japan*
[4]*Institute of Oceanography, VAST, Vietnam*
[5]*Research Institute for Basic Sciences, Jeju National University, Jeju 63000, Republic of Korea*

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ABSTRACT

The review critically examines the brown algal genus *Padina* (family Dictyotaceae), emphasizing its biodiversity, distribution, and potential applications, particularly in Vietnam. Globally, *Padina* species inhabit tropical and temperate coastal ecosystems, playing crucial ecological roles in primary production and as habitats for marine organisms. In Vietnam, nine species of *Padina* have been documented, yet their taxonomic diversity and applications remain underexplored. This synthesis highlights the morphological traits, ecological significance, and geographic distribution of *Padina* in Vietnam, with a focus on its potential in pharmaceuticals, nutraceuticals, cosmeceuticals, and bioremediation. Biochemical analyses reveal bioactive compounds such as terpenoids, polyphenols, and fucoidans, which demonstrate antioxidant, antimicrobial, and anti-inflammatory activities. These properties underscore *Padina's* potential for natural product development in pharmaceutical and cosmetic industries. Despite this promise, research in Vietnam has predominantly centered on taxonomic and ecological aspects, with limited studies on biochemical and economic applications. The review identifies critical gaps in understanding species boundaries, phylogenetic relationships, and ecological roles. It advocates for advanced morphological and molecular studies, including molecular barcoding, to uncover cryptic diversity and resolve taxonomic ambiguities. Future research directions include exploring *Padina*'s reproductive biology, dispersal mechanisms, and responses to environmental stressors such as climate change. Additionally, investigations into its ecological roles, particularly as bioindicators of environmental health and agents for pollution mitigation, are essential. Addressing these gaps will enhance knowledge of *Padina* biodiversity and support the sustainable management and utilization of this valuable marine resource in Vietnam.

Keywords: *Padina*, dictyotaceae, brown algal, Vietnam, diversity.

[*/**]Corresponding author at: Institute of Marine Environment and Resources, 246 Da Nang, Ngo Quyen, *Hai Phong 180000, Vietnam. E-mail addresses*: quannv@imer.vast.vn/cvcarp@gmail.com

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INTRODUCTION

The genus *Padina* (Dictyotaceae, Phaeophyceae) serves as a primary producer and contributes to the biodiversity [1] and productivity [2] of coastal ecosystems. They primarily provide shelter, food, and nursery habitats for various marine organisms, thereby supporting these ecosystems' overall health and functioning [3]. *Padina* species are distributed in tropical to temperate coasts [4–7]. The genus morphology is characterized by its distinctive fan-shaped or ribbon-like thalli, often exhibiting concentric striations and proliferous growth patterns [5, 8]. Taxonomically, 59 accepted species names, three accepted varieties, and one accepted format are in the current database. In synonymy, there are 20 species names and two variety names [9], with new species and taxonomic revisions being proposed regularly due to ongoing research efforts.

There has been a growing interest in the economic potential of *Padina* species, driven by the recognition of their unique biochemical compositions and bioactive compounds [10]. Several studies have investigated the presence of valuable secondary metabolites, such as terpenoids, polyphenols, and polysaccharides, in *Padina* species, which exhibit a range of biological activities, including antioxidant, antimicrobial, and anti-inflammatory properties [11, 12]. These findings have sparked interest in the potential use of *Padina* species in developing natural products for pharmaceutical, nutraceutical, and cosmeceutical applications [13, 14].

In Vietnam, *Padina* species are distributed along the entire country's coastline in diverse marine ecosystems [15]. According to the most recent comprehensive marine floral checklist [16, 17], nine *Padina* species have been documented in Vietnam. Despite their ubiquity and economic potential, *Padina* species in Vietnam remain comparatively different from other parts of the world, particularly regarding their full taxonomic diversity and potential applications. Prior research endeavors have predominantly centered on taxonomic inventories and ecological assessments, with a limited scope of investigation into detailed morphological taxonomy [18]. This gap in comprehensive morphological studies presents an opportunity for more in-depth research to elucidate the fine-scale diversity and phylogenetic relationships within the genus *Padina* on the Vietnamese coast.

This review aims to provide a comprehensive overview of the current knowledge regarding the diversity and potential of *Padina* species in Vietnam. It will synthesize existing literature on the taxonomic diversity, morphological characteristics, and distribution patterns of *Padina* species found in Vietnamese waters. Furthermore, this review will explore the potential applications of these algae, highlighting their prospective uses in pharmaceuticals, food and agriculture, bioremediation, and other emerging fields. By consolidating and critically evaluating the available information, this review seeks to identify knowledge gaps and potential areas for future research, ultimately contributing to a better understanding and sustainable utilization of this valuable marine resource in Vietnam.

MATERIALS AND METHODS

To investigate the diversity and potential applications of *Padina*, we conducted a comprehensive literature review utilizing multiple databases and resources. Our primary sources included the AlgaeBase (https://www.algaebase.org), Google Scholar (https://scholar.google.com), Web of Science (https://clarivate.com/webofsciencegroup), ScienceDirect (https://www.sciencedirect.com), Scopus (https://www.scopus.com), PubMed (https://pubmed.ncbi.nlm.nih.gov), and other relevant online databases. We searched for published studies reporting species lists and occurrence data from field surveys and research related to bioactive compounds, biological activities, and the environmental significance of *Padina* species. Additionally, we examined historical taxonomic studies and gene sequence data available on GenBank (https://www.nc-bi.nlm.nih.gov/genbank).

To ensure a comprehensive review, we also included unpublished works such as M. Phil. and Ph.D. theses and technical reports from universities and scientific institutes in the Vietnamese Science & Technology Publishing Database (https://sti.vista.gov.vn). Studies were selected based on the following criteria: (1) Publication in peer-reviewed journals, conference proceedings, project reports, or abstract compilations; (2) Reporting of species lists from field collections. From the selected studies meeting these criteria, we extracted the following data into our database: Species name, morphology, habitat, distribution, available genetic data, and economic and medicinal, environmental significance.

Biogeographical patterns were analyzed using a presence and absence data set to compare species across oceans, regions, and provinces using a Bray-Curtis similarity index [19] multivariate analysis implemented in Primer V.6 software [20], based on the compiled data for the region. This methodology allowed for a systematic and thorough examination of the current knowledge of *Padina* species, diversity, distribution, and potential applications, providing a solid foundation for our research findings and subsequent discussions.

TAXONOMY AND SYSTEMATICS

Following Algaebase [9], the systematics of the genus *Padina* adhere to the taxonomic framework proposed by Guiry (2024) [21], providing a structured and scientifically robust approach to its categorization within the brown algae. According to this classification, *Padina* belongs to the phylum Heterokontophyta, subphylum Ochrophytina, which houses a diverse range of algae characterized by their unique pigmentation and photosynthetic apparatus. *Padina* is further classified under Phaeophyceae within this subphylum, which is known for its distinct brown algae members. Moving down the taxonomic hierarchy, *Padina* is part of the subclass Dictyotophycidae and the order Dictyotales, which includes species recognized for their flattened, dichotomously branched thalli. Within this order, *Padina* is placed in the family Dictyotaceae and the tribe Zonarieae. This classification underscores the genus's close evolutionary ties to other genera within the Dictyotales and highlights its unique ecological adaptations.

The history of taxonomy and systematic research of the genus *Padina* has undergone extensive revisions and debates over decades of research. Early taxonomic studies, such as Adanson (1763) [22] and J.V. Lamouroux (1809) [23], proposed initial classifications based solely on morphological observations of thallus forms, coloration patterns, and reproductive and cell structures. However, subsequent research revealed significant phenotype contains due to environmental factors within *Padina* populations, rendering morphology an unreliable taxonomic criterion (e.g., *P. melemele* I.A. Abbott & Magruder and *P. fasciata* Ni-Ni-Win, M. Uchimura & H. Kawai in Japan and *P. maroensis* Ni-Ni-Win, I.A. Abbott & H. Kawai in Hawaii, which were kept as *P. boryana* Thivy, *P. minor* Yamada, and *P. moffittiana* I.A. Abbott & Huisman, respectively) [8, 24]. Despite considerable advancements in analytical techniques, species delineation in *Padina* remains challenging.

With the advent of molecular techniques, particularly DNA sequencing, our understanding of *Padina*'s diversity and evolutionary relationships has significantly improved. Phylogenetic analyses based on multiple molecular markers (e.g., *rbc*L, *psb*A, and ITS) have revealed cryptic diversity within the genus, leading to the recognition of several new species and the re-evaluation of existing taxa: *P. okinawaensis* Ni-Ni-Win, S. Arai & H. Kawai from Ryukyu Islands (Japan), Hawaii, Indonesia and Thailand, *P. undulata* Ni-Ni-Win, S. Arai & H. Kawai, *P. terricolor* Ni-Ni-Win, M. Uchimura & H. Kawai, *P. fasciata* from Ryukyu Islands (Japan) [25]; *P. ditristromatica* Ni-Ni-Win & H. Kawai and *P. pavonicoides* Ni-Ni-Win & H. Kawai [26]; Additionally, *P. gracilis* Ni-Ni-Win, M. Tokeshi & H. Kawai and *P. lata* Ni-Ni-Win, M. Tokeshi & H. Kawai from Myanmar [24].

Integrative taxonomic approaches, combining molecular data with detailed morphological and anatomical observations, have proven invaluable in resolving species boundaries and clarifying taxonomic relationships within *Padina* [5, 27, 28]. These studies have highlighted the importance of considering multiple lines of evidence and the potential for convergent evolution and morphological homoplasies.

Recent taxonomic revisions have resulted in the description of several new *Padina* species, particularly from understudied regions such as the Indo-Pacific and the Mediterranean Sea, these are *P. imbricata* Ni-Ni-Win, H. Shimabukuro & H. Kawai, *P. lutea* Ni-Ni-Win, M. Uchimura & H. Kawai*, P. moffittianoides* Ni-Ni-Win, M. Uchimura & H. Kawai and *P. nitida* Ni-Ni-Win, Hanyuda, M. Uchimura & H. Kawai, or new records in the Mediterranean Sea include: *P. gymnospora* (Kützing) Sonder, or Italia coast: *P. pavonicoides* and *P. tetrastromatica* Hauck [24, 29]. Furthermore, molecular data has shed light on biogeographic patterns and evolutionary processes, such as long-distance dispersal, vicariance events, and hybridization, which have shaped the current distribution and diversity of the genus [6, 7].

Despite these advances, *Padina*'s taxonomy and systematics remain challenging due to the complexity of morphological variation, incomplete sampling, and the potential for cryptic speciation. Ongoing research efforts incorporating advanced molecular techniques (e.g., genomics and transcriptomics), ecological data, and detailed morphological investigations are crucial for resolving remaining taxonomic uncertainties and elucidating the evolutionary history of this ecologically important seaweed genus.

MORPHOLOGY AND CLASSIFICATION

The genus *Padina* consists of species that present either erect or prostrate thalli, typically attached to substrates through a rhizoidal holdfast. These thalli can grow up to 30 cm (e.g., *P. macrophylla* Ni-Ni-Win, M. Uchimura et H. Kawa) in length and are commonly flattened (complanate) and fan-shaped (flabellate) [8], with some exhibiting a lacerated (torn or irregular) appearance towards their base. The thallus is calcified to a greater or lesser extent on both surfaces or only on the upper (superior) surface (facing the inrolled margin) [26]. One of the critical characteristics of the genus is its growth pattern, which begins with a marginal row of apical cells within an involute apical fold directed towards the upper (or inner) thallus surface [9]. The thalli of *Padina* species vary in thickness from 2 (e.g., *P. japonica* Yamada and *P. minor*) [30] to 8 (*P. crassa* Yamada) or ten cell layers (*P. arborescens* Holmes) [5], depending on the specific species. A notable morphological trait includes the presence of characteristic whitish hairs, frequently observed in concentric lines on one or both thallus surfaces. The outermost layer of cortical cells contains numerous discoid chloroplasts, essential for the alga's photosynthetic activity. Reproductive structures, such as sporangial sori, are arranged in concentric rows or isolated patches between the hairlines on one or both thallus surfaces. The presence of an indusium, a protective covering over the sori, can vary between species. Mature sporangia are ovoid to pyriform, measuring 80–170 µm in height, and each produces four spores. The gametophytes of *Padina* species are predominantly dioecious, although some species may be monoecious. Oogonial sori are also arranged in concentric rows, while antheridial sori, often whitish, follow a similar organization. These structures are partially embedded in the thallus and contain multiple tiers of locules [9, 13].

Several morphological and reproductive traits serve as important criteria for species differentiation within the genus *Padina*. These include: (1) The number of cell layers in the thallus, which may range from two layers to as many as four or more; (2) The occurrence of hairlines on one or both thallus surfaces; (3) The visibility of hairlines, whether they are conspicuous or inconspicuous, particularly on the superior surface where they appear as pale or faint scars; (4) The arrangement of hairlines on both surfaces, either at equal or unequal distances, or irregularly positioned; (5) The distribution of reproductive sori on one or both thallus surfaces; (6) The relationship between sori and hairlines, with sori either positioned distally close to, abutting, or irregularly spreading between the hairlines; (7) The degree of embedding of the sori in the thallus, ranging from superficial placement to partial or deep embedding within the cell layers; (8) The number of rows of sori between the hairlines, typically one or two rows; (9) The presence or absence of an indusium, with variations sometimes observed between the tetrasporophyte and gametophyte stages in certain species (Fig. 1 & Table 1) [24].

BIODIVERSITY AND BIOGEOGRAPHY

In the world

This analysis, based on data derived from Algaebase, reveals the global distribution of Padina species, with 61 taxa recorded across 119 countries and territories worldwide. The analysis provides comprehensive insights into this genus's geographic spread and diversity, excluding the two species, *Padina zonata* Gaillon and *Padina phasiana* Bory, which lack specific distribution data. The data highlights that the highest concentration of Padina species is observed in Australia, with 39 taxa recorded, accounting for approximately 64% of the global diversity (Fig. 2). The United States follows closely with 37 taxa, and India ranks third with 30. These numbers underscore the significant presence of Padina in tropical and subtropical marine environments, particularly within the Indo-Pacific region. A deeper look into the geographical distribution shows that the tropical-subtropical waters of the Western Pacific exhibit the most incredible species diversity. This finding aligns with previous studies, such as Ni-Ni-Win's 2021 research, which also emphasized the richness of Padina species in these regions [7].

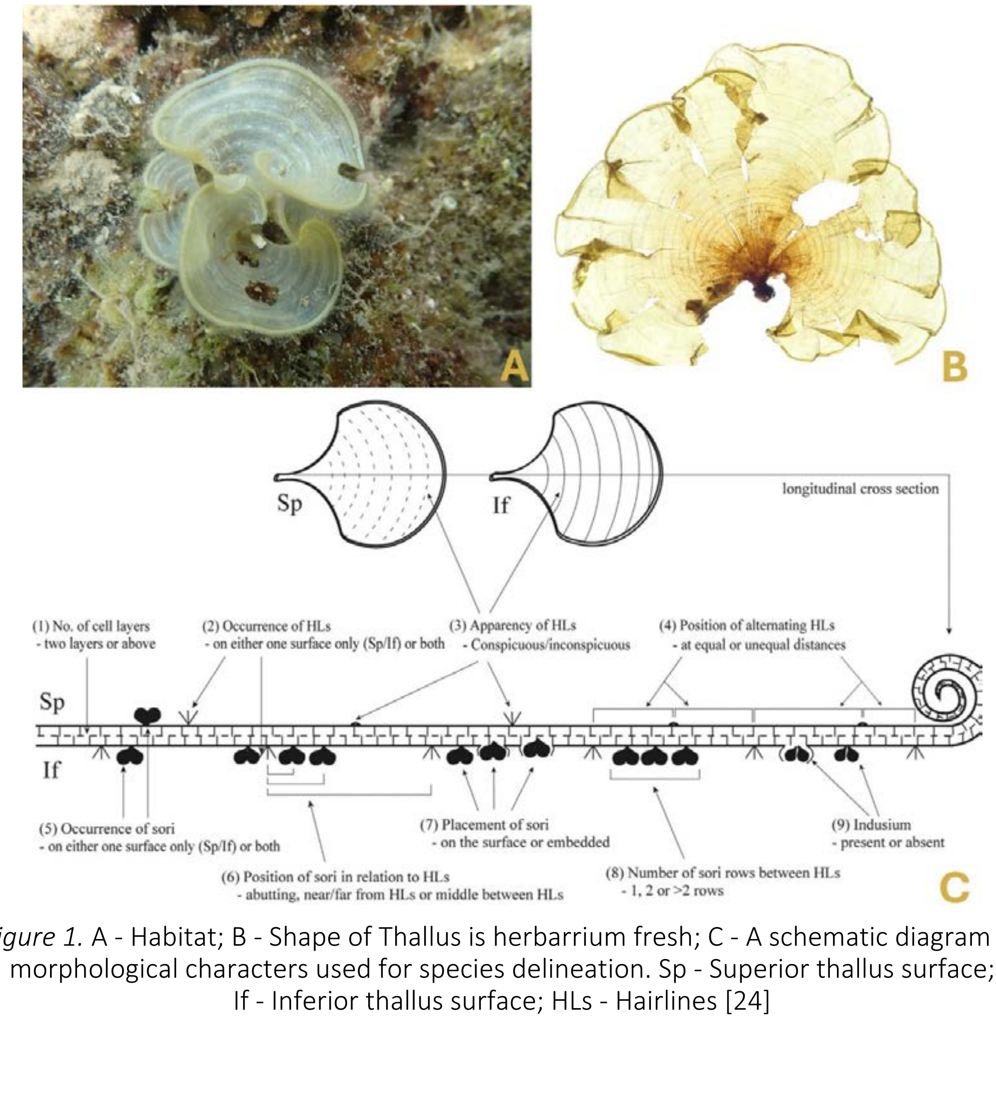

Figure 1. A - Habitat; B - Shape of Thallus is herbarrium fresh; C - A schematic diagram of morphological characters used for species delineation. Sp - Superior thallus surface; If - Inferior thallus surface; HLs - Hairlines [24]

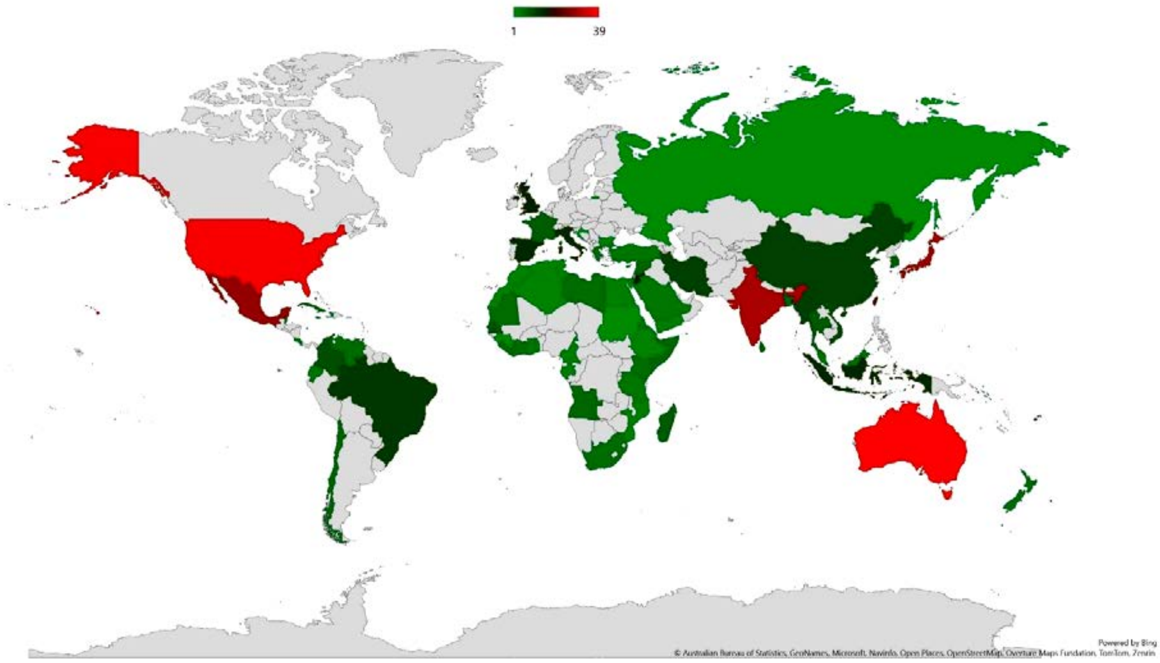

Figure 2. Global mapping of Padina species biodiversity

The dataset and network graph analysis offer a profound insight into the richness and global distribution of *Padina* species (Fig. 3). The network graph vividly illustrates the intricate connections between various species and their geographical regions, highlighting the global spread of these algae. Notably, the dense and complex web of connections among species like *Padina gymnospora* (recorded in 72 countries and territories), *Padina pavonica* (70), and *Padina boryana* (56) underscores their wide distribution and presence across diverse ecological zones, from tropical to temperate regions, reflecting their ecological flexibility and the ability to thrive in multiple environments.

Additionally, Figure 4 depicts the occurrence of 13 synonyms associated with five taxonomically accepted *Padina* species spread across 59 countries. These findings provide critical insights into the genus's taxonomic complexity and nomenclatural variations. Synonyms often arise from historical misidentifications, regional differences in naming conventions, or incomplete taxonomic revisions. Such inconsistencies can obscure accurate assessments of species distribution and diversity, potentially leading to overestimating species richness or underestimating their global range. Resolving these synonymies through careful taxonomic revision is vital to improve the accuracy of biodiversity assessments and biogeographical analyses.

Taxonomic reconciliation is essential in biodiversity studies for widely distributed groups like *Padina*. Misidentifications or inconsistent naming practices across different regions can lead to inflated species counts, skewed ecological interpretations, and flawed conservation priorities. By identifying and correcting the 13 synonymies, this study ensures that the global distribution data for the *Padina* species is reliable, reflecting their true prevalence and ecological significance. Such taxonomic clarity is essential for accurate ecological modeling, enabling more precise assessments of species distributions, habitat preferences, and responses to environmental stressors.

The role of *P. gymnospora, P. pavonica,* and *P. boryana* as a "keystone species" is exciting. Its widespread presence and extensive connectivity suggest that it plays a critical role in maintaining the ecological balance and stability of many coastal marine ecosystems.

Keystone species are integral to ecosystem function, as their influence on the structure and health of their habitats is disproportionately large relative to their abundance [31–35]. In this case, *P. gymnospora, P. pavonica,* and *P. boryana* likely contribute significantly to nutrient cycling, habitat formation, and the overall resilience of marine ecosystems, especially in coral reefs and coastal zones.

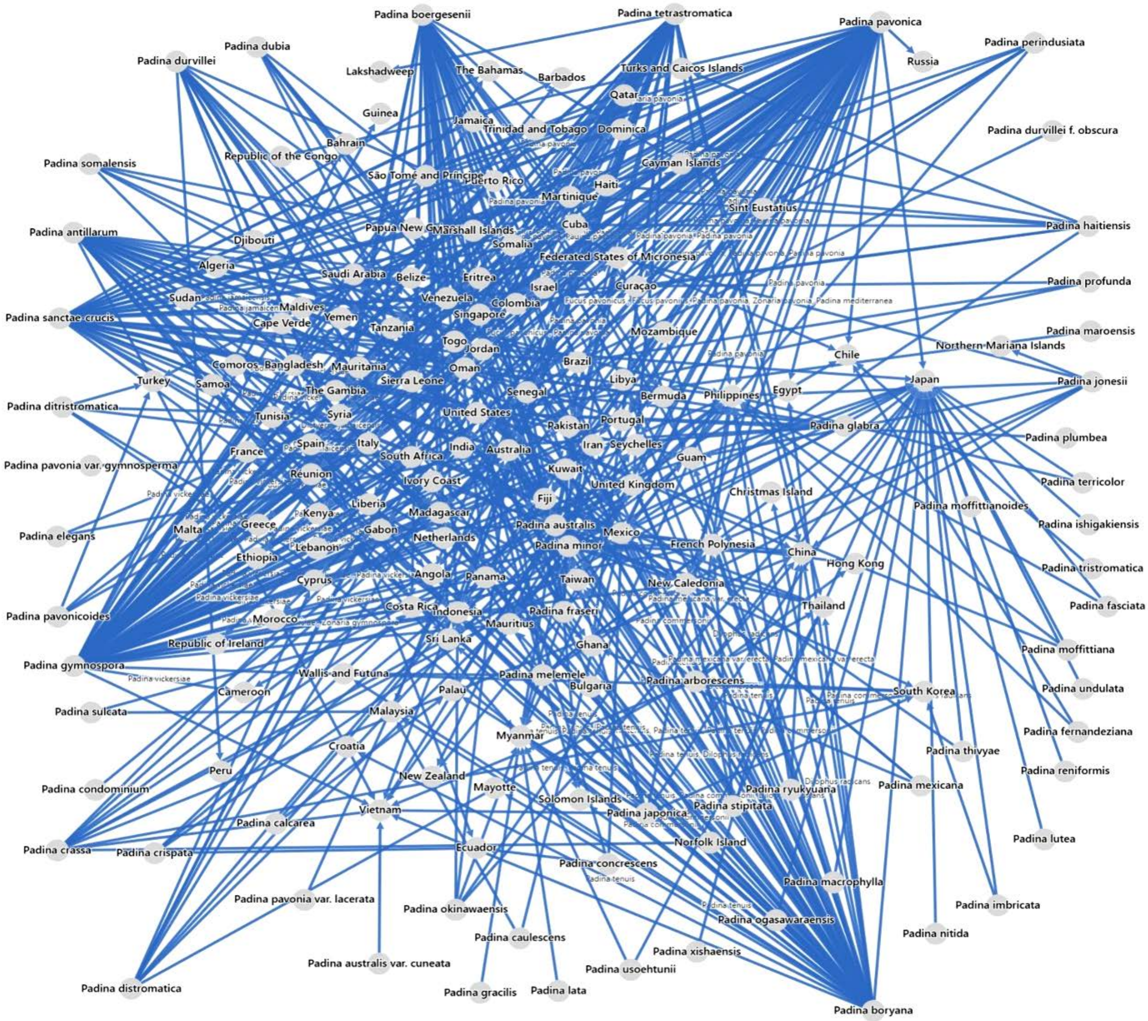

Figure 3. Network graph of knowledge clusters on Padina's global distribution

The emphasis on the significance of keystone species highlights their ecological importance and underscores the necessity for further research into lesser-known species. While species like *P. gymnospora, P. pavonica,* and *P. boryana* are well documented, the potential roles of less common species remain largely unexplored. These lesser-known species may provide crucial insights into the specific ecological functions they fulfill, their interactions with other marine organisms, and their responses to environmental changes.

The analysis also highlights the distribution of 19 species confined to a single country, providing an intriguing aspect of biogeographical differentiation. Japan, for instance, hosts 8 of these species, reflecting its unique marine ecosystems. Australia is home to 3 species, while the United States records 2. Other countries such as Myanmar (2 species), Vietnam, China, Chile, and Brazil (1 species each) also have species unique to their territories. These findings suggest the existence of localized ecological niches supporting the development and persistence of specific *Padina* species (Fig. 5).

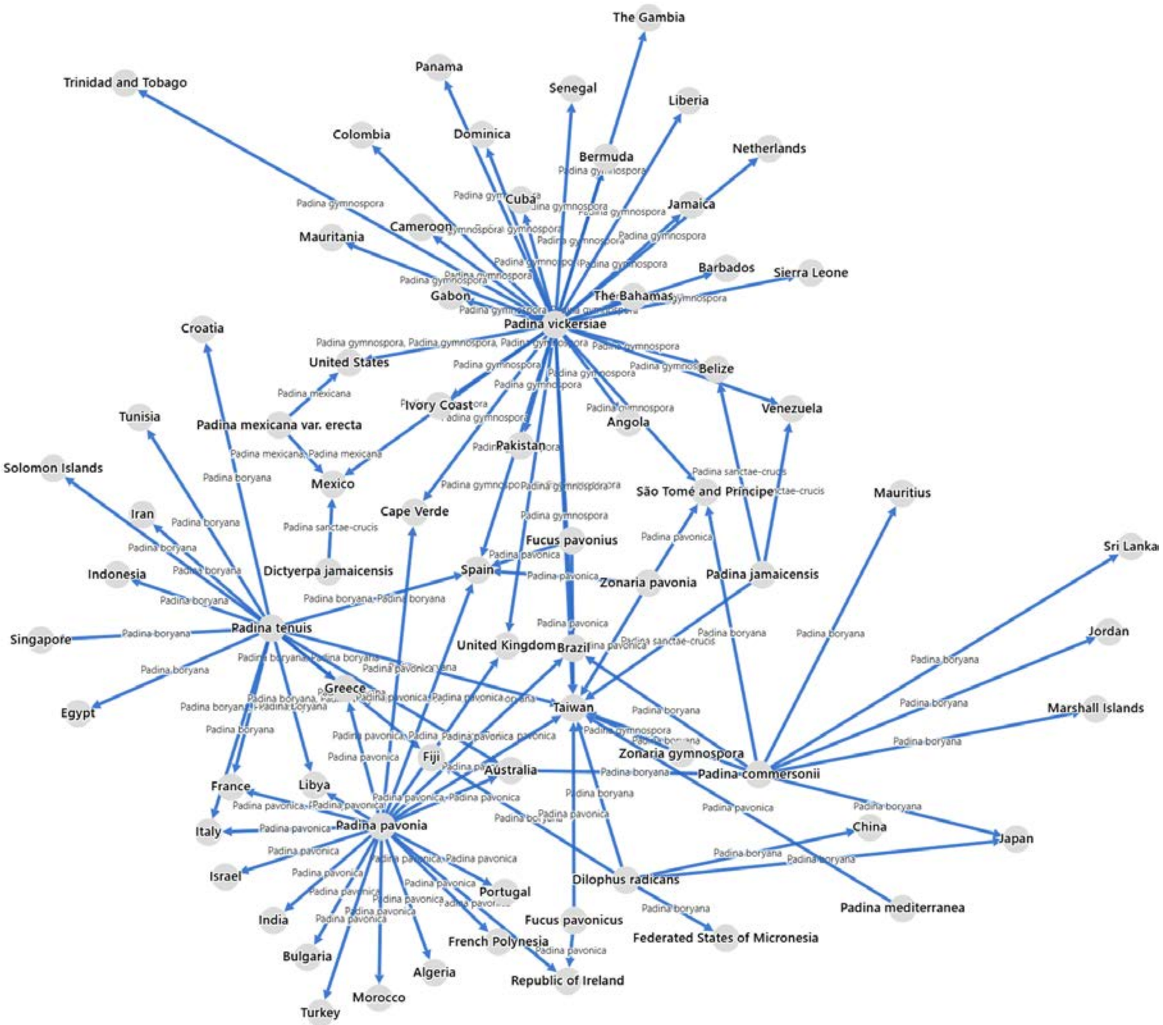

Figure 4. Synonyms of some *Padina* species recorded of 59 countries in the world

The restricted distribution of these species, especially in the Pacific region, raises an important question regarding the potential factors limiting their spread beyond these areas. Is the limited distribution due to environmental constraints, such as ocean currents, salinity levels, or temperature gradients, or are other factors at play, such as historical biogeography or evolutionary adaptation to local conditions?

Interestingly, the restricted distribution observed in the Pacific contrasts with findings from Ni Ni Win's previous research, which reported that *Padina* species found in the Mediterranean Sea and the Atlantic Ocean exhibit similarly limited distributions confined to those specific marine regions [7]. This raises further questions about the biogeographical dynamics of *Padina* species across different oceanic regions. For example, why do some species of *Padina* exhibit wide-ranging distributions across the Pacific and Indian Oceans, while others are more restricted to specific oceanic basins like the Mediterranean or the Atlantic? Moreover, the confined distribution of some species within specific regions highlights the possibility of endemism, where species evolve and adapt to unique local conditions, preventing their migration to other areas. This could explain why certain species of Padina are found exclusively in countries like Japan, Australia, or the United States and not in neighboring regions with similar environmental conditions.

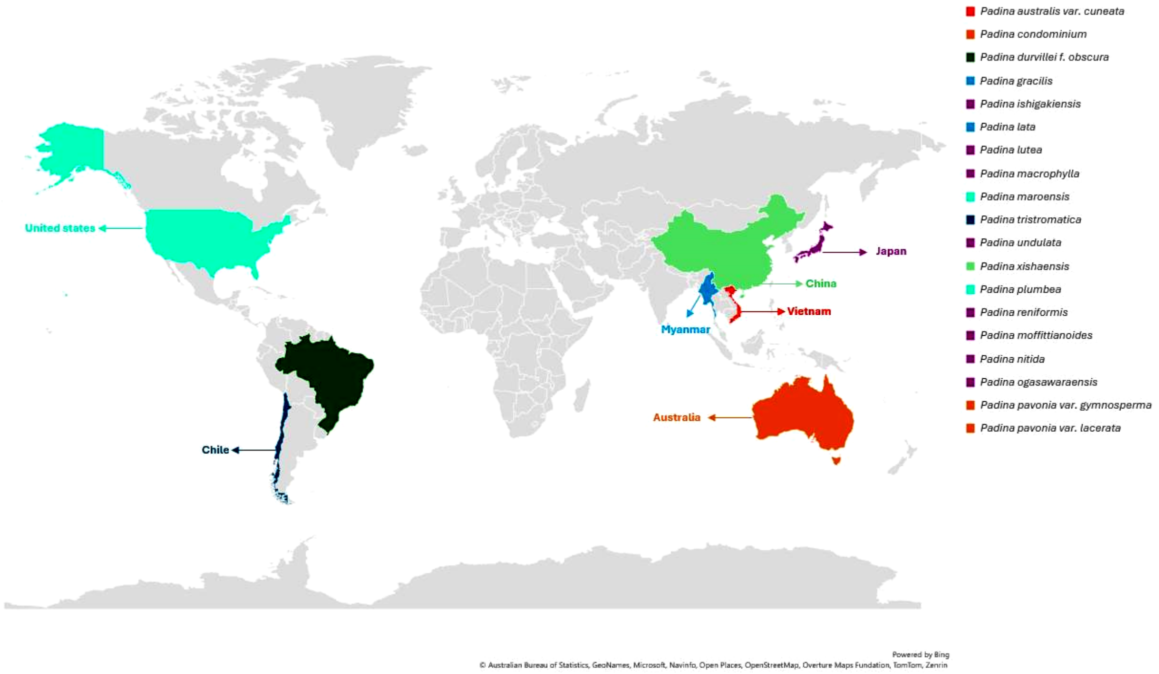

Figure 5. Geographic distribution of endemic *Padina* species recorded in select countries worldwide

In the East Vietnam Sea

In regional comparisons within Southeast Asia (East Vietnam Sea or South China Sea) using a species distribution on Algaebase [9], including countries with maritime borders with the East Sea (China), the Philippines exhibits the highest biodiversity, with 17 recorded species of *Padina*. This is followed by Indonesia and Myanmar, each with 12 species. Vietnam and China house nine species, while Thailand has 7, Singapore 6, and Malaysia 3 species. Cambodia has no recorded presence of *Padina* species, which could be attributed to unfavorable environmental conditions or a lack of comprehensive research data. This distribution underscores the rich marine biodiversity in the Philippines and highlights potential gaps in ecological data for regions like Cambodia (Fig. 6).

In examining the East Vietnam Sea region, which encompasses coastal nations such as China, a diverse array of *Padina* species has been documented. The species with the broadest distribution *are P. australis* and *P. boryana*, found in seven countries. Close behind, *P. antillarum*, *P. minor*, and *P. tetrastromatica* are present in six countries. *P. gymnospora* and *P. japonica* are recorded in four countries, while P. *distromatica*, *P. fraseri*, and *P. sanctae-crucis* are found in three. Several species are noted in two countries, including *P. arborescens*, *P. crassa, P. jonesii, P. okinawaensis, P. ryukyuana, P. sulcata*, and *P. usoehtunii*. Additionally, various species are documented in just one country within this region, such as *P. boergesenii, P. calcarea, P. australis* var. *cuneata*, *P. fasciata, P. fernandeziana, P. gracilis, P. lata, P. moffittiana, P. terricolor*, and *P. xishaensis*.

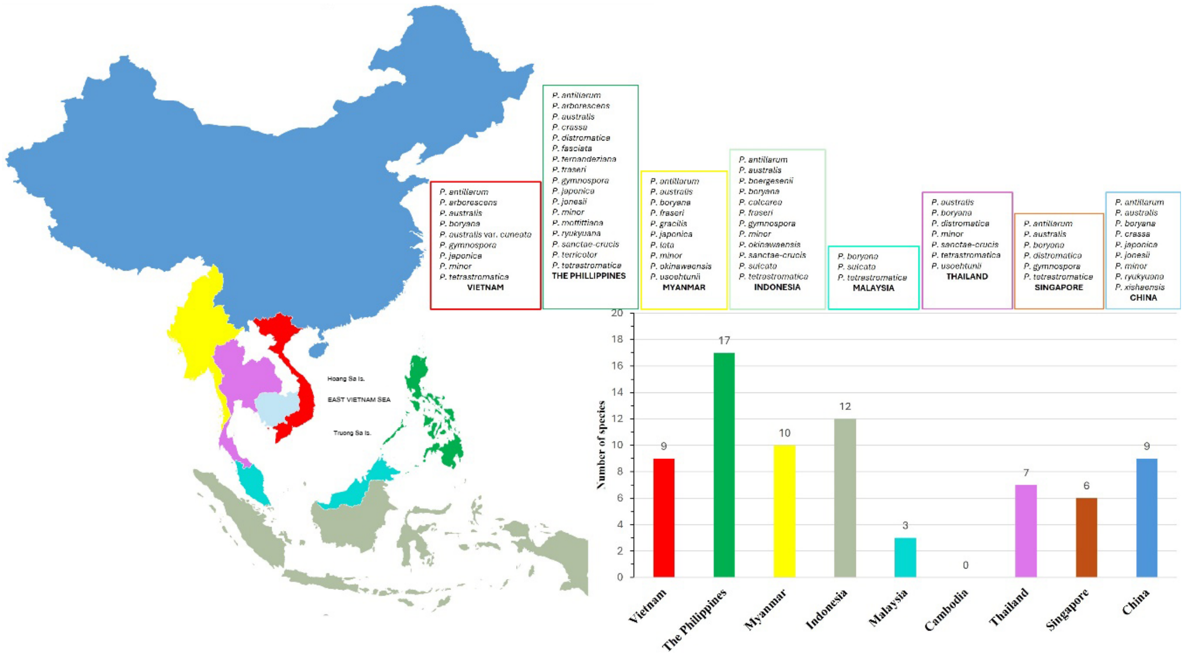

Figure 6. Biodiversity of the genus *Padina* in the East Vietnam Sea

When comparing the geographical distribution of these species based on the Bray-Curtis similarity model, neighboring countries tend to exhibit higher similarities in species composition (Fig. 7). This pattern underscores the influence of geographic proximity on the distribution and similarity of marine flora in the East Vietnam Sea region.

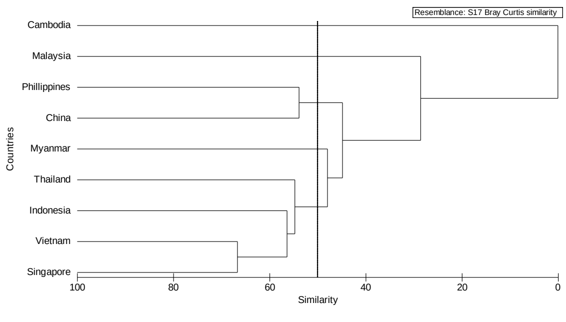

Figure 7. Similarity of composition of *Padina* in the East Vietnam Sea

In Vietnam

The initial catalog of marine macroalgae in Vietnam was made by Loureiro in 1790 [36], describing 20 species. However, no records of the *Padina* species were found. The first comprehensive list of *Padina* species was documented by Dawson in 1954 [37], which included *Padina commersonii* Bory (now considered a synonym of *Padina boryana* Thivy). Subsequently, Pham Hoang Ho in 1969 [38] included only three species: *P. boryana, P. australis,* and *P. gymnospora*. Nguyen Huu Dinh et al., (1993) [39] further expanded the list by adding two species found in northern Vietnam: *P. terastromatica* and *P. crassa*. In 2013 and 2016, the research of Nguyen Van Tu [40], Phang et al., [41] listed six *Padina* species in Vietnam. In their list, *P. antillarum* replaced *P. terastromatica*, and *P. crassa* was synonymous with *P. gymnospora*. A variety, *P. australis* var. *cuneata*, was added to the list. By 2020, Belous et al., [16] published an updated list of seaweed species from central to southern Vietnam, which included nine *Padina* species. This list introduced *P. japonica* and *P. arborescens* as new records for the Vietnamese flora, although specimens had not been previously published. In 2023, Linh et al., [17] synthesized an updated list based on publications about the marine flora of Vietnam and data on the distribution of algae from

AlgaeBase (www.algaebase.org), confirming the presence of nine *Padina* species in Vietnam, consistent with Belous's list in 2020. All published *Padina* specimens were differentiated by morphological characteristics. However, there is a significant lack of, or no mention of, associated voucher specimen data. This has led to many previous records being considered ambiguous, reflecting inaccurate identifications or poorly understood diversity. Species delineation has been confused by overlapping morphological features, hybridization, incomplete lineage sorting, and complex speciation processes.

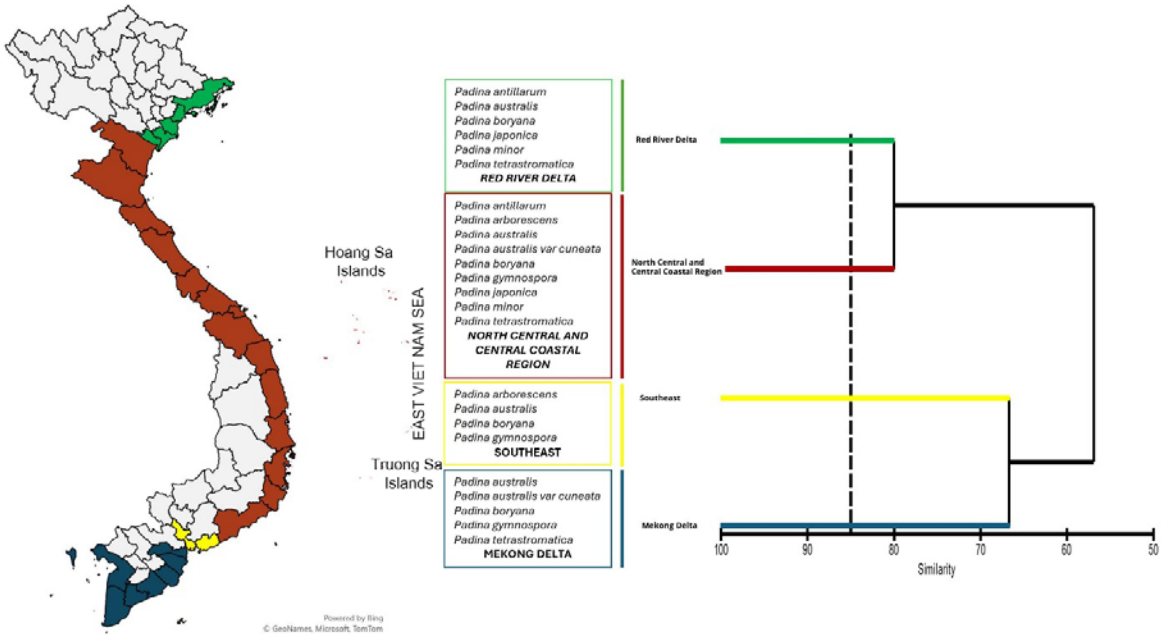

Figure 8. Biodiversity and biogeography of *Padina* in the coastal area of Vietnam based on economic region

Vietnamese *Padina* diversity represents only a fraction of the genus's overall diversity in tropical Indo-Pacific areas. Research on *Padina* distribution has been conducted in 12 of the 28 coastal provinces in Vietnam. According to Vietnam's economic regions[1], the North Central and Central Coastal region exhibits the highest diversity, with all nine recorded species present. This aligns with the findings of Linh et al., (2023) [17], who identified the central region as having the highest marine algae distribution in the country. Following this, the Red River Delta region has the second-highest diversity with six recorded species, the Mekong Delta ranks third, and the Southeast region has the lowest diversity with four species (Fig. 8). This lower diversity in the Southeast can be attributed to its relatively more minor coastal area.

Alpha diversity seems highest in Khanh Hoa (6 species) and Quang Ninh (5 species), likely due to their wide habitat heterogeneity and reef-sheltered conditions. Regarding biogeography in Vietnam, *P. australis* is found throughout the country. In contrast, *P. antillarum* is recorded only from Thanh Hoa to Quang Ninh, *P. arborescens* from Binh Thuan to Ba Ria Vung Tau, and *P. australis* var. *cuneata*, which requires further subspecies verification, is found in Khanh Hoa and Vung Tau. However, the lack of a holotype herbarium specimen for *P. australis* var. *cuneata* currently hinders definitive identification (Fig. 9).

[1] Resolution No. 81/2023/QH15 dated January 9, 2023, on National Master Plan for 2021–2030 with vision scheduled for 2050.

Future biodiversity research is needed to elucidate the genetic diversity, reproductive strategies, population connectivity, and adaptive capabilities of *Padina* in Vietnam and conduct biogeographical studies. Initial research efforts could concentrate on the North-South transitional zone as a case study to provide foundational insights [15].

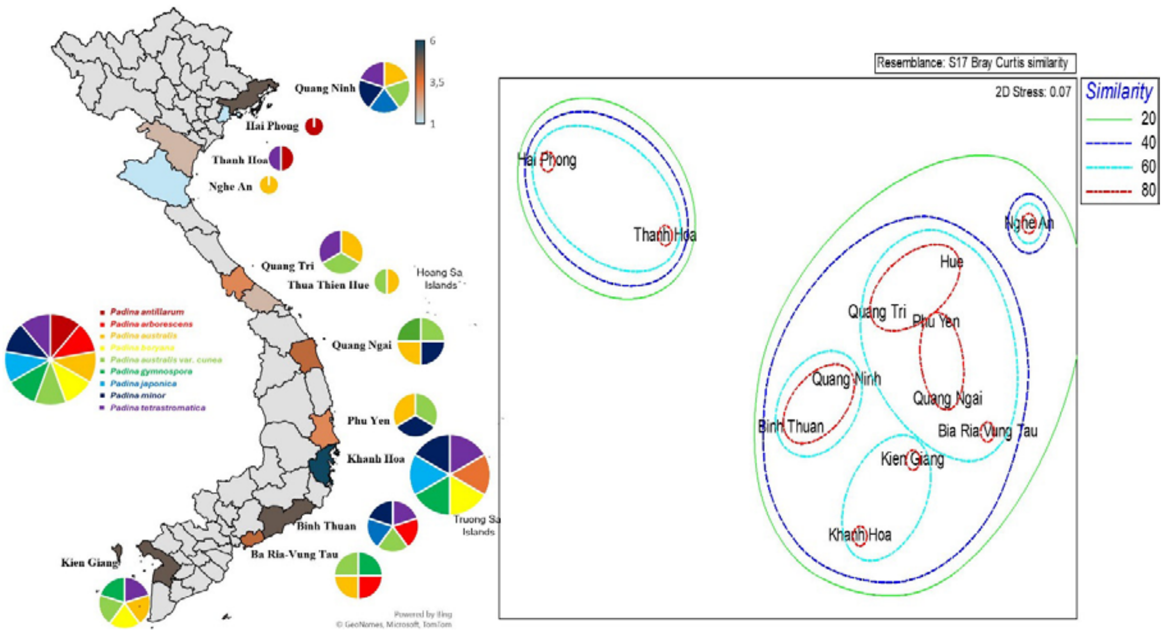

Figure 9. Biodiversity and biogeography of *Padina* in the coastal area of Vietnam based on provinces

POTENTIAL APPLICATIONS AND USES

Economic and medicinal potential

Padina species, commonly found in various folk applications related to human nutrition, are recognized as a valuable reservoir of vitamins, carotenoids, proteins, and minerals. Recently, pharmaceutical markets have witnessed the emergence of medicines containing marine algae-derived products to treat diverse ailments [42]. Among these bioactive compounds, purified fucoidans from *Padina tetrastromatica* and *Padina boergesenii* Allender and Kraft have been investigated for their potential wound-healing properties. In a rat model, a 2% topical ointment formulated with these fucoidans demonstrated improvements in key healing indicators, including angiogenesis, collagen fiber formation, and epidermis regeneration [43]. Additionally, members of the genus *Padina* harbor halogenated compounds, such as bromophenols, uncommon in higher plants. These compounds exhibit unique pharmacological effects, disrupting intracellular calcium ions within the endocrine system [13, 44, 45].

Rushdi et al., (2021) reported that approximately 27% (17 species) of known *Padina* seaweeds have been investigated for bioactivities. However, detailed chemical analysis is limited to 25.3% (16 species) [13, 46]. Notably, polar fractions are believed to be the primary source of these activities (Fig. 10).

Environmental significance

As a predominant macroalga in tropical intertidal habitats, *Padina* provides vital ecosystem services and has utility as a bioindicator species for monitoring environmental changes along coastlines [47]. They cycle nutrients, especially nitrogen and phosphorus, which they uptake from the water column. *Padina* photosynthesis contributes significantly to coastal primary productivity [2] and carbon fixation [48–50]. Thalli and detrital matter from *Padina* provide food and physical habitats for diverse invertebrates, fish, and epiphytic organisms [51]. Fauna associated with *Padina* populations, including amphipods, harpacticoid copepods, polychaetes, and juvenile mollusks, find refuge among its branches [52]. However, the *Padina* populations are vulnerable to human impacts like eutrophication, pollution, sedimentation, and climate change. Increased turbidity from sediment runoff reduces light penetration, affecting *Padina* growth and depth limits. Nutrient enrichment can shift algal dominance towards faster-growing opportunistic species. *Padina*'s responses can, therefore, serve as early indicators of declining coastal water quality and environmental changes [53].

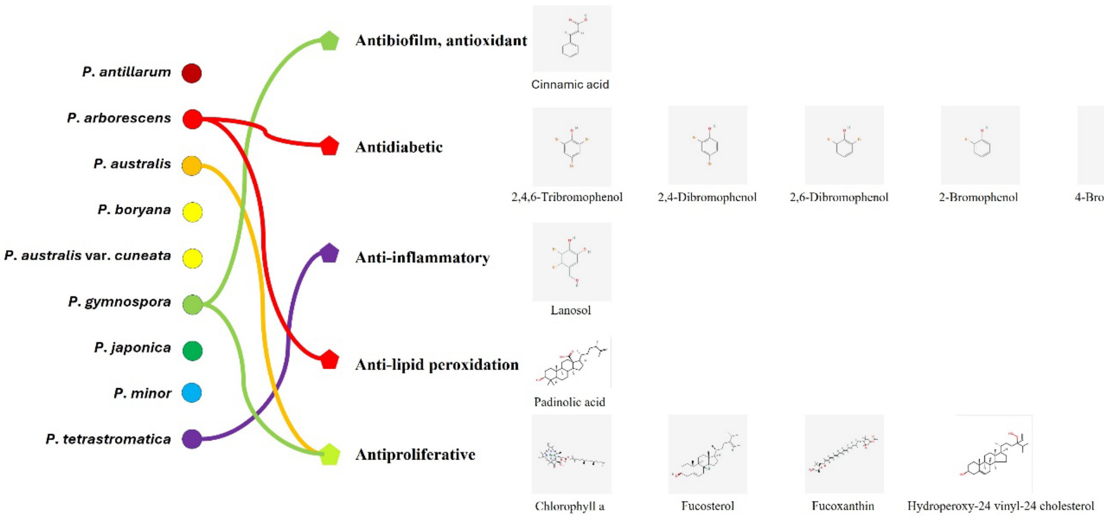

Figure 10. Biological activity reported in some *Padina* species

Targeted monitoring of *Padina* population dynamics, growth rates, morphologies, and chemical signatures from across environmental gradients can provide insights into health indicators of coastal ecosystem. *Padina* shows utility as a tropical bioindicator species equivalent to kelp species in temperate habitats. Conserving *Padina* diversity and abundance is integral for maintaining healthy and productive coastal ecosystems, fisheries productivity, and community livelihoods in coastal areas.

KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

A comprehensive analysis of research trends on *Padina* seaweed from 1965 to 2024 reveals a burgeoning interest in this marine organism [54]. This surge is evident in the increasing number of published studies, reflecting the growing scientific community's attention to *Padina*'s unique characteristics and potential applications (Fig. 11). Regarding taxonomic research, 63 *Padina* species have been documented between 1827 and 2021. Notably, from 2010 to the present, the period has witnessed a significant acceleration in species identification, accounting for 32% of the recorded species.

The geographical distribution of newly identified *Padina* species highlights the organism's global presence. Japan has emerged as a hotspot for *Padina* diversity, with 11 newly recorded species. Additionally, five species have been discovered in the East Sea region (Myanmar, Indonesia, Thailand, Malaysia, and the Philippines), two in the Mediterranean Sea, one in Pakistan, and one in Hawaii.

This surge is attributed to the advent and widespread adoption of molecular biology tools in taxonomic studies. Integrating molecular biology techniques with traditional morphological analysis has revolutionized *Padina* taxonomy, as seen in other members of Phaeophyceae [55–58]. This combined approach offers enhanced precision and resolution, enabling valid identification and classification of *Padina* species, particularly those with subtle morphological differences [5, 7, 25, 29] (Fig. 12).

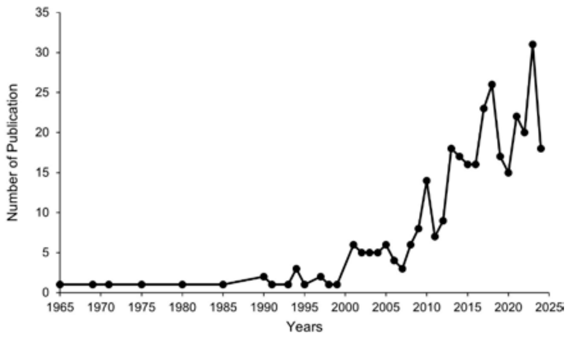

Figure 11. Timelines of the number of publications in *Padina* from 1965 to 2024

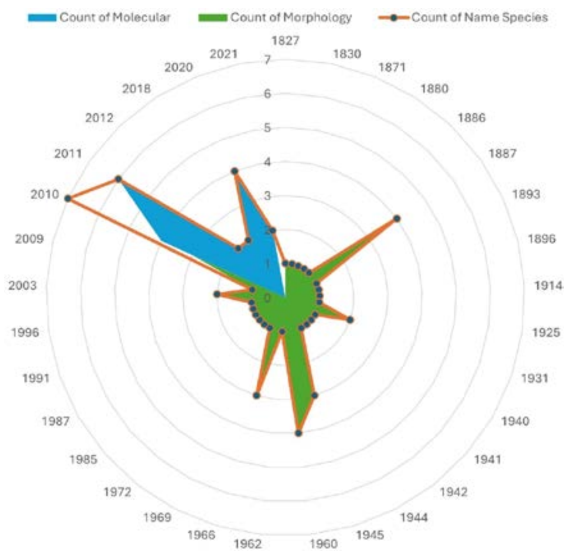

Figure 12. The study recorded of Padina species in the world from 1827 to 2021

According to GenBank data, a total of 1,769 gene sequences from 49 species (78% of the total species) of the genus *Padina* have been deposited, with no sequences recorded from Vietnam (updates to August 2024) [59]. This presents a significant opportunity and challenge for future research on Vietnamese *Padina*. When there are considerable knowledge gaps regarding the genus *Padina* in Vietnam that need to be addressed through targeted research initiatives. Taxonomically, species delimitation requires further verification using integrative approaches that combine morphology, molecular studies, cytology, reproductive biology, and biogeography. Molecular barcoding of extensive Padina collections from diverse habitats could uncover potentially undescribed or cryptic diversity. Resolving these taxonomic issues is crucial for accurately accumulating data on species distributions, ecology, and applications.

The number of nucleotide sequences of *Padina* species deposited in GenBank is shown in Figure 13. *P. arborescence* exhibits the most extensive sequence coverage with 282 sequences, followed by *P. australis* (103) and *P. boergesenii* (81). Conversely, species like *P. terricolor, P. stipitata*, and *P. gymnospora* have limited representation, with fewer than 10 sequences each. Furthermore, target gene preferences are seen for *Padina* molecular studies. *Cox*3 and *rbc*L were the most frequently used, appearing in 46 and 43 species, respectively. This suggests their effectiveness in resolving genetic variation within *Padina*. *Psb*A and *psa*A were also commonly employed for 19 and 20 species, respectively, indicating their potential utility for specific research questions. COI was used for 14 species, while 18S saw less extensive use for three species. Therefore, in future molecular studies, the use of *Cox*3 and *rbc*L is currently considered optimal for investigating *Padina* species, as these gene regions have demonstrated the highest effectiveness in resolving genetic variation across a wide range of species. Their consistent utilization in numerous studies underscores their reliability, making them the preferred choice for comprehensive genetic analyses within this genus.

Little is known about the population genetics, reproductive strategies, early life histories, and dispersal capabilities of *Padina* species in Vietnam, which hinders effective spatial management and conservation efforts. Understanding genetic connectivity patterns between populations along the coast can inform the creation of networks of marine protected areas. Controlled field and laboratory experiments are essential to quantify *Padina*'s responses and tolerances to environmental parameters such as temperature, salinity, irradiance, nutrients, and pollution. These findings would improve predictive distribution models under climate change scenarios involving warming seas and intensified storms.

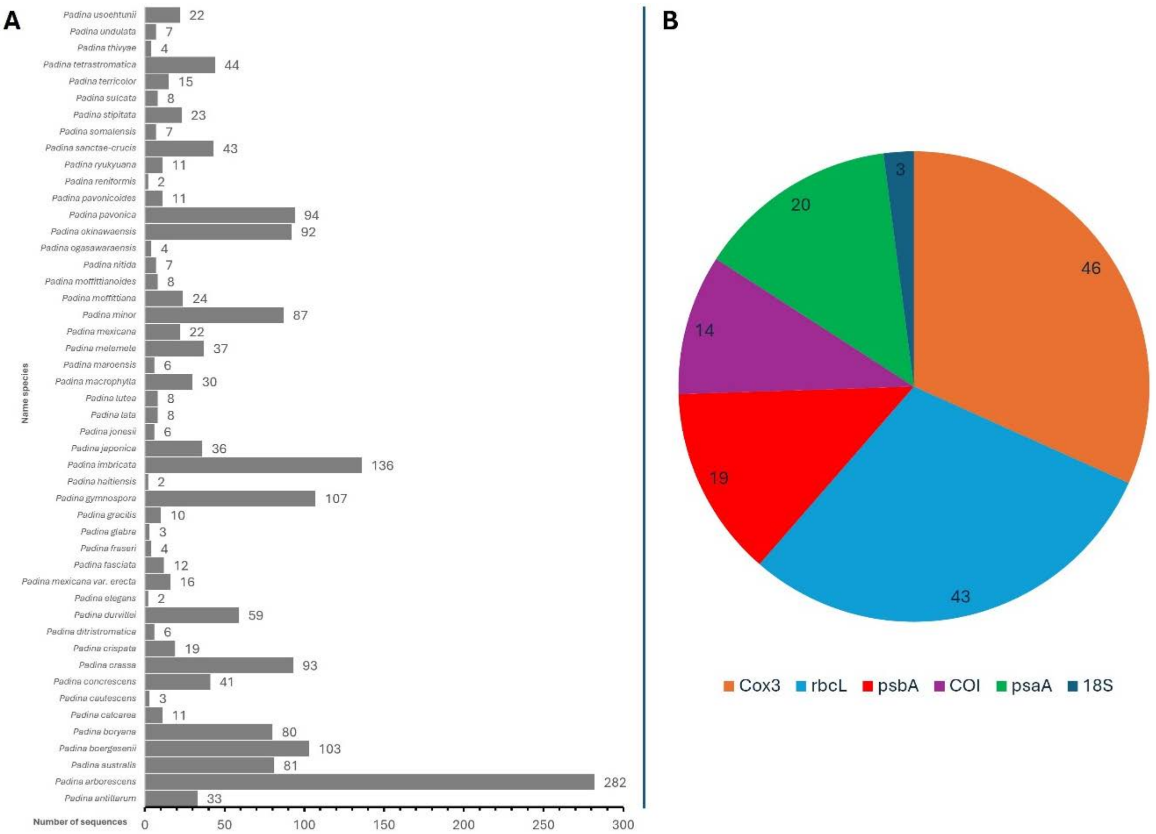

Figure 13. The number of nucleotides sequence of *Padina* species deposited in GenBank (A) and number of species of each primer deposited on the database (B)

Comprehensive surveys are still needed to delineate the geographic ranges of *Padina* species conclusively. Fifteen coastal provinces in Vietnam have yet to be studied and evaluated for *Padina* distribution. Mapping spatial and bathymetric distributions can identify diverse hotspots and threatened populations for protection. Coordinated monitoring efforts can detect population declines before local extirpations occur. Further taxonomic research is also necessary to understand the diversity of the species in Vietnam. Recent studies on the genus *Lobophora* in Dictyotaceae, for instance, have resulted in the documentation of nine new species for Vietnam and two new species for science [60], or *Ulva* has seven new species for Vietnam and one new species for science [61]. Similarly, detailed taxonomic studies on *Padina* could discover new species, contributing to our understanding of marine biodiversity and the ecological significance of these species.

Research on cultivation techniques, bioactive compounds, and nutritional values is crucial to developing biotechnological applications of *Padina* in Vietnam. Trials on farming, biofertilizer preparations, and cosmeceutical extractions can sustainably unlock *Padina*'s commercial potential.

Addressing these research gaps through collaborative initiatives between academia, industry, and government will provide the knowledge base to effectively conserve, sustainably utilize, and manage *Padina* resources in Vietnam. Such findings will enable science-based policymaking regarding coastal zone planning and mariculture development.

Targeted monitoring of *Padina* population dynamics, growth rates, morphologies, and chemical signatures across environmental gradients can provide insights into coastal ecosystem health. *Padina* can serve as a foundation species in tropical habitats, similar to kelp species in temperate to boreal habitats. Conserving *Padina* diversity and abundance is integral for maintaining healthy and productive coastal ecosystems, fisheries productivity, and the livelihoods of coastal communities.

This review provides a comprehensive overview of the current knowledge regarding the brown algal genus *Padina* in Vietnam, highlighting its biodiversity, biogeography, potential applications, and future research directions. The study of *Padina* in Vietnam represents a microcosm of the broader challenges and opportunities in phycological research globally.

CONCLUSION

Vietnam coastal waters harbor at least 9 *Padina* species, with *P. australis* being the most widely distributed. This diversity, while significant, likely underestimates the actual species richness due to the limitations of traditional morphological identification methods. Applying integrative taxonomic approaches, combining molecular phylogenetics with detailed morphological and ecological observations, is crucial for resolving species boundaries and uncovering potential cryptic diversity within the genus.

The biogeographical patterns of *Padina* in Vietnam reflect the country's diverse coastal environments, with the highest species richness observed in the central region. This distribution pattern aligns with broader trends in marine algal diversity along the Vietnamese coast and underscores the importance of habitat heterogeneity in shaping biodiversity.

Padina species play vital ecological roles in Vietnam's coastal ecosystems, contributing to primary productivity, providing habitat for various marine organisms, and potentially serving as bioindicators of environmental change. The genus also shows promise for various biotechnological applications, including pharmaceutical, nutraceutical, and cosmeceutical products, highlighting the need for sustainable exploitation strategies.

However, significant knowledge gaps persist, particularly in understanding the genetic diversity, population connectivity, and adaptive capabilities of the *Padina* species in Vietnam. The absence of molecular data for Vietnamese *Padina* populations in global databases represents a critical research opportunity. Future studies should prioritize:

1. Comprehensive molecular phylogenetic analyses of *Padina* populations along the Vietnamese coast.
2. Detailed investigations into the reproductive biology and early life history stages of *Padina* species.
3. Ecological studies to quantify the responses of *Padina* to environmental stressors, including climate change.
4. Development of cultivation techniques for economically promising species.
5. Exploration of novel bioactive compounds and their potential applications.

Addressing these research priorities will advance our understanding of Padina in Vietnam and contribute to global phycological knowledge. Moreover, it will provide crucial data for evidence-based conservation strategies and sustainable resource management in the face of increasing anthropogenic pressures on coastal ecosystems.

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