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Phylogenetic relationships of *Rosenvingea* (Scytosiphonaceae, Phaeophyceae) from Vietnam based on *cox3* and *psaA* sequences

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The taxonomic status and the distribution of *Rosenvingea* species need attention because of the difficulties in morphological identification in the laboratory as well as in the field. We analyzed mitochondrial *cox3* and plastid *psaA* gene sequences from *Rosenvingea* species from Vietnam, Mexico and Panama in combination with morphological examinations. Our results confirmed the occurrence of *R. intricata* and *R. orientalis* in Vietnam. *R. intricata* formed dense decumbent mats with many flat branches, often inter-adhesive, and was up to 5 cm in diameter. *R. orientalis* thalli were up to 18 cm long with narrow (less than 2 mm in width) tubular to compressed fronds. Both *cox3* and *psaA* phylogenies revealed the non-monophyly of the genus *Rosenvingea*, as reported previously for other scytosiphonacean genera.

Key Words: brown algae; *cox3*; Ectocarpales; *psaA*; *Rosenvingea*; taxonomy; Vietnam

INTRODUCTION

The genus *Rosenvingea* Børgesen is a tropical to subtropical genus of scytosiphonacean brown algae that includes seven currently accepted species (Guiry and Guiry 2014). *Rosenvingea* is distinguished by its erect thalli with alternate or dichotomous branches, an apical to subapical meristem, a single plastid and prominent pyrenoid in vegetative cells, hollow medulla, and phaeophycean hairs and plurangial sori scattered on the thallus surface (Børgesen 1914, Abbott and Huisman 2004, Norris 2010, West et al. 2010). Børgesen (1914) established the genus with *R. sanctae-crucis* Børgesen as the type and included three other species in the genus *Asperococcus* J. V. Lamouroux as follows, *R. fastigiata* (Zanardini) Børgesen, *R. intricata* (J. Agardh) Børgesen, and *R. orientalis* (J. Agardh) Børgesen. Subsequently three more species were added: *R. antillarum* (P. Crouan & H. Crouan) M. J. Wyn-

ne, *R. floridana* (W. R. Taylor) W. R. Taylor, and *R. nhatrangensis* E. Y. Dawson (Dawson 1954, Taylor 1955, Wynne 1997). However, the species circumscription in *Rosenvingea* is very confused. For example, *R. sanctae-crucis*, the type of *Rosenvingea*, was suggested to be conspecific with *R. orientalis* (Earle 1969, Littler and Littler 2000, Wynne 2005, Dawes and Mathieson 2008, Nelson and Wilcox 2010). Wynne (1997) treated *R. floridana* as a synonym of *R. antillarum*, although Norris (2010) considered that both species are not conspecific. The cosmopolitan or endemic distribution patterns of *Rosenvingea* species are, accordingly, doubtful.

The first molecular analysis of *Rosenvingea* was based on sequences of *rbcL* and *rbcS* from Japanese specimen of *R. intricata* (Kogame et al. 1999) and was followed with *psaA* by Cho et al. (2006). Subsequently, *R. intricata* was



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analyzed with additional seven genes, plastid *atpB*, *psaA*, and *psbA*, and mitochondrial *atp9*, *cox1*, *cox3*, and *nad11* (Silberfeld et al. 2010). The second species included in molecular taxonomic study is *R. orientalis* that was sequenced for *psaA* and *cox3* (West et al. 2010, Lee et al. 2014).

Dawson (1954) described *R. nhatrangensis* as a new species and also reported *R. orientalis* in Nha Trang, Vietnam. Afterwards, *R. intricata* was reported in southern Vietnam (Pham 1969) and additional record from northern Vietnam (Nguyen et al. 1993). Another species, *R. fastigiata* was also reported to occur in northern Vietnam (Nguyen et al. 1993, 2013). We collected two species of *Rosenvingea* in Nha Trang during March and April 2011. Together with morphological observations, we analyzed both *cox3* and *psaA* gene from these specimens so as to provide a better understanding of species diversity and phylogenetic relationships in *Rosenvingea*.

MATERIALS AND METHODS

Representative *Rosenvingea* specimens were collected from mid intertidal zone in Cam Ranh Bay, Nha Trang, Vietnam, and specimens collected in Mexico and Panama were also included in analyses for comparison (Table 1). All specimens collected were mounted on herbarium sheets. Small parts of the specimens were cut for molecular analyses. Photographs were taken with a DP-71 camera (Olympus, Tokyo, Japan) attached to a BX-51 microscope (Olympus). Voucher specimens were deposited at the Department of Biology, Chungnam National University, Daejeon, Korea (CNUK).

Information on specimens used for the molecular study is given in Table 1. DNA extraction, PCR amplification, and sequencing followed Boo et al. (2011b). Primer pairs for the amplification and sequencing of each gene were F49–R20 for *cox3* (Boo et al. 2010, 2011a) and *psaA130F-psaA940R* and *psaA870F-psaA1760R* for *psaA* (Yoon et al. 2002).

Phylogenies of *cox3* and *psaA* datasets were reconstructed using maximum likelihood (ML), including *Ectocarpus siliculosus* (Dillwyn) Lyngbye and *Pylaiella littoralis* (Linnaeus) Kjellman as outgroups. ML analyses were performed with RAxML v.7.2.8 (Stamatakis 2006) using the GTR + GAMMA + I model. We used 200 independent tree inferences, applying options of automatically optimized subtree pruning regrafting rearrangement and 25 distinct rate categories in the program to identify the best tree. Statistical support for each branch was obtained

from 1,000 bootstrap replications with the same substitution model.

Bayesian inference was performed for individual datasets with MrBayes v.3.2.1 (Ronquist et al. 2012) using the Metropolis-coupled Markov Chain Monte Carlo (MC3) with the GTR + GAMMA + I model. For each matrix, two million generations of two independent runs were performed with four chains and sampling trees every 100 generations. The burn-in period was identified graphically by tracking the likelihoods at each generation to determine whether they reached a plateau. The 40,002 trees sampled at the stationary state were used to infer Bayesian posterior probabilities (BPP).

RESULTS

Phylogeny of *cox3* and *psaA*

A 627-nucleotide portion of *cox3* was aligned for 40 sequences including 12 *Rosenvingea* and one previously published sequence of *R. intricata* from New Caledonia. Variable sites occurred at 284 positions (45.3%), of which 222 positions (35.4%) were parsimoniously informative. *R. intricata* differed by 32-39 bp (5.5-6.7%) from *Rosenvingea* sp. collected in Hawaii and Mexico and by 40-45 bp (6.9-7.7%) from *R. orientalis* from Vietnam. There was a difference of 42 bp (7.2%) between *Rosenvingea* sp. and *R. orientalis*. One sequence from New Caledonia (GQ368280) was highly divergent from other sequences of *R. intricata* (28 bp, 4.8%). Pairwise divergence within *R. intricata* (except the New Caledonia specimen) ranged up to 8 bp (1.4%). The phylogenetic relationships of *Rosenvingea*, using *cox3* sequences, showed a well-supported Scytosiphonaceae consisting of eight genera (Fig. 1). There was no resolution of the phylogenetic relationships among sequences of *R. intricata* sequences.

A 1,488-nucleotide portion of the *psaA* gene was compared across 28 sequences including six *Rosenvingea* and three previously published sequences collected from New Caledonia, Mexico and Japan. Variable sites occurred at 392 positions (26.3%), of which 256 positions (17.2%) were parsimoniously informative. *R. intricata* differed by 88-98 bp (6.3-7.0%) from *R. orientalis*. The *psaA* sequence of *R. intricata* from the Vietnamese specimen differed by 11 bp (0.8%) from the specimen from Panama, 54 bp (3.9%) from the New Caledonian specimen, and 92 bp (6.6%) from the Japanese specimen. In the *psaA* tree (Fig. 2), *R. intricata* from Vietnam and Panama together with *R. intricata* from New Caledonia formed a monophyletic

Table 1. Specimens and *cox3* and *psaA* sequences of the taxa included in this study

Species, collection sites, and date	Voucher	GenBank accession No.	
		<i>cox3</i>	<i>psaA</i>
<i>Rosenvingea intricata</i> (J. Agardh) Børgeesen			
Playa La Concha, La Paz, Mexico; Mar 31, 2009	CNU6705	KM587011	-
Central America, unknown	CNU7199	KM587012	-
Cam Ranh Bay, Nha Trang, Vietnam; Mar 31, 2011	CNU8204	KM587013	-
Cam Ranh Bay, Nha Trang, Vietnam; Apr 9, 2011	CNU8206	KM587014	-
Cam Ranh Bay, Nha Trang, Vietnam; Mar 29, 2011	CNU8207	KM587015	KM587023
Cam Ranh Bay, Nha Trang, Vietnam; Mar 17, 2011	CNU8208	KM587016	-
Isla Canal de Afuera, Veraguas, Panama; Jan 14, 2011	CNU27444	KM587017	-
Isla Canal de Afuera, Veraguas, Panama; Jan 14, 2011	CNU30473	KM587018	KM587024
Ricaudy, New Caledonia; Jun 27, 2008	-	GQ368280	GQ368338
<i>R. orientalis</i> (J. Agardh) Børgeesen			
Cam Ranh Bay, Nha Trang, Vietnam; Apr 9, 2011	CNU8205	KM587019	KM587025
Boca del Cielo, Chipas, Mexico; Mar 11, 2009	-	-	KC588969
<i>Rosenvingea</i> sp.			
Oahu Kaneohe Bay, Hawaii; Jul 2, 2007	HS2779	KM587020	-
Canal de San Lorenzo, Baja California Sur., Mexico; Dec 5, 2013	CNU25002	KM587021	-
<i>Chnoospora implexa</i> J. Agardh	-	GQ368273	-
<i>C. minima</i> (K. Hering) Papenfuss	-	KF700277	DQ239773
<i>Colpomenia bullosa</i> (Saunders) Yamada	-	JQ918795	DQ239775
<i>C. claytoniae</i> S. M. Boo, K. M. Lee, G. Y. Cho & W. Nelson	-	HQ833783	-
<i>C. durvillei</i> (Bory de Saint-Vincent) Ramírez	-	JQ918801	-
<i>C. ecuticulata</i> Parsons	-	HQ833776	-
<i>C. expansa</i> (De A. Saunders) Y. P. Lee	-	HQ833780	-
<i>C. peregrina</i> Sauvageau	-	HQ833767	DQ239776
<i>C. phaeodactyla</i> M. J. Wynne & J. N. Norris	-	-	DQ239777
<i>C. ramoas</i> Taylor	-	JQ918789	-
<i>C. sinuosa</i> (Mertens ex Roth) Derbès & Solier	-	HQ833778	AY372950
<i>C. tuberculata</i> De A. Saunders	-	HQ833773	-
<i>C. wynnii</i> K. M. Lee, R. Riosmena-Rodriguez, K. Kogame & S. M. Boo	-	KF700278	-
<i>Hydroclathrus clathratus</i> (C. Agardh) Howe	-	KF700313	DQ239778
<i>H. tenuis</i> C. K. Tseng et Lu	-	KF700314	DQ239780
<i>Melanosiphon intestinalis</i> (De A. Saunders) M. J. Wynne			
Kruz of Island, Sitka, Alaska; Jul 13, 2006	PE730	KM587022	-
Bay of Fundy, New Brunswick, Canada; Jan 11, 2007	-	-	KF281540
<i>Myelophycus cavus</i> Tanaka et Chihara	-	KF700315	DQ239781
<i>M. simplex</i> (Harvey) Papenfuss	-	KF700316	AY372952
<i>Petalonia binghamiae</i> (J. Agardh) Vinogradova	-	KF700317	DQ239782
<i>Scytosiphon canaliculatus</i> (Setchell et Gardner) Kogame	-	KF700321	KF281548
<i>S. complanatus</i> (Rosenvinge) Doty	-	-	KF281560
<i>S. dotyi</i> Wynne	-	KF700322	DQ239785
<i>S. gracilis</i> Kogame	-	KF700323	DQ239786
<i>S. tenellus</i> Kogame	-	KF700323	-
Outgroup			
<i>Ectocarpus siliculosus</i> (Dillwyn) Lyngbye	-	FP885846	FN564540
<i>Pylaiella littoralis</i> (Linnaeus) Kjellman	-	NC003055	AY119724

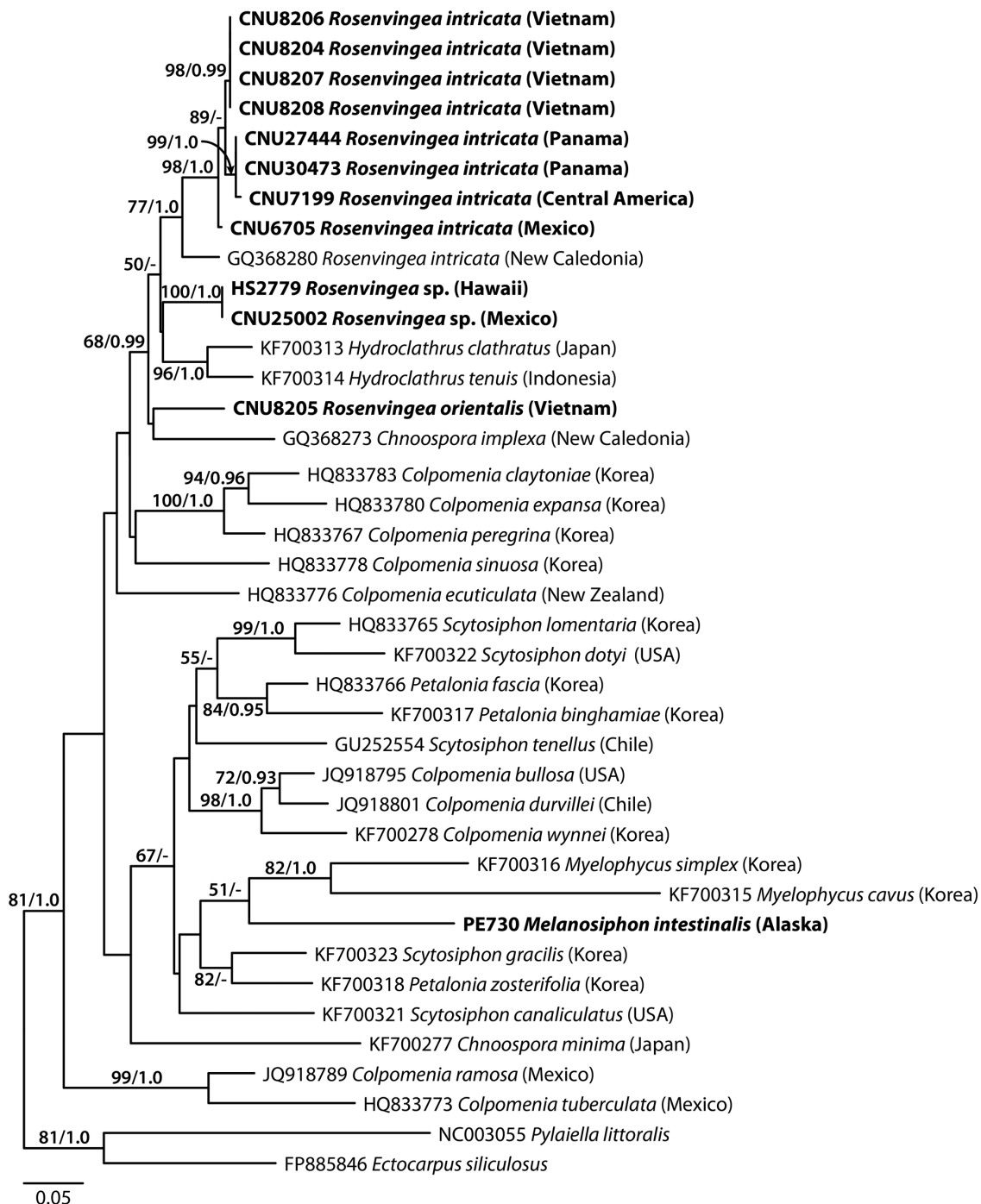


Fig. 1. Maximum likelihood tree of *Rosenvingea* inferred from the phylogenetic analysis of *cox3* sequences. Values shown near branches are bootstrap values (1,000 iterations) and Bayesian posterior probabilities. Only bootstrap values >50% and Bayesian posterior probabilities >0.90 are shown.

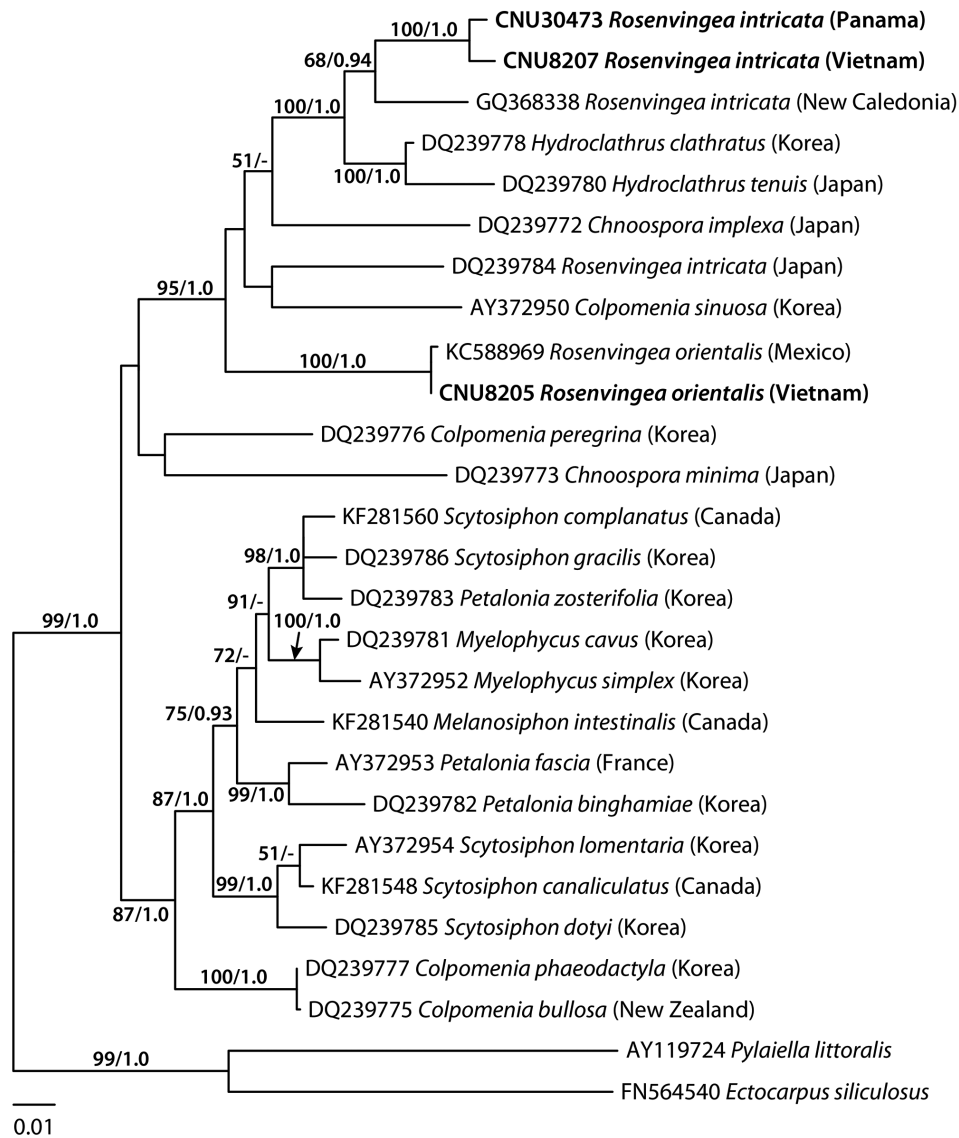


Fig. 2. Maximum likelihood tree of *Rosenvingea* inferred from the phylogenetic analysis of *psaA* sequences. Values shown near branches are bootstrap values (1,000 iterations) and Bayesian posterior probabilities. Only bootstrap values >50% and Bayesian posterior probabilities >0.90 are shown.

group with moderate support values (68% for ML and 0.94 for BPP). This group was closely related to *Hydroclathrus* with maximum support values. One published sequence of *R. intricata* collected from Japan did not belong to the group of samples from Vietnam and Panama, but rather sister to *Colpomenia sinuosa* (Mertens ex Roth) Derbès & Solier. *R. orientalis* was placed in the clade that includes *R. intricata*, *Hydroclathrus clathratus* (C. Agardh) Howe, *H. tenuis* C. K. Tseng & Lu, *Chnoospora implexa* J. Agardh, and *Colpomenia sinuosa* (95% for ML and 1.0 for BPP).

Morphology of *Rosenvingea intricata* and *Rosenvingea orientalis*

Thalli of *R. intricata* were brown to dark brown in color, up to 5 cm in height and 5 mm in diameter (Fig. 3A-D). The thalli formed a dense decumbent mat with many branches that were often inter-adhesive. The axes were cylindrical to compressed, subdichotomously to irregularly lobed, 4-6 mm in diameter, becoming narrower distally. Apices of branches were mostly rounded.

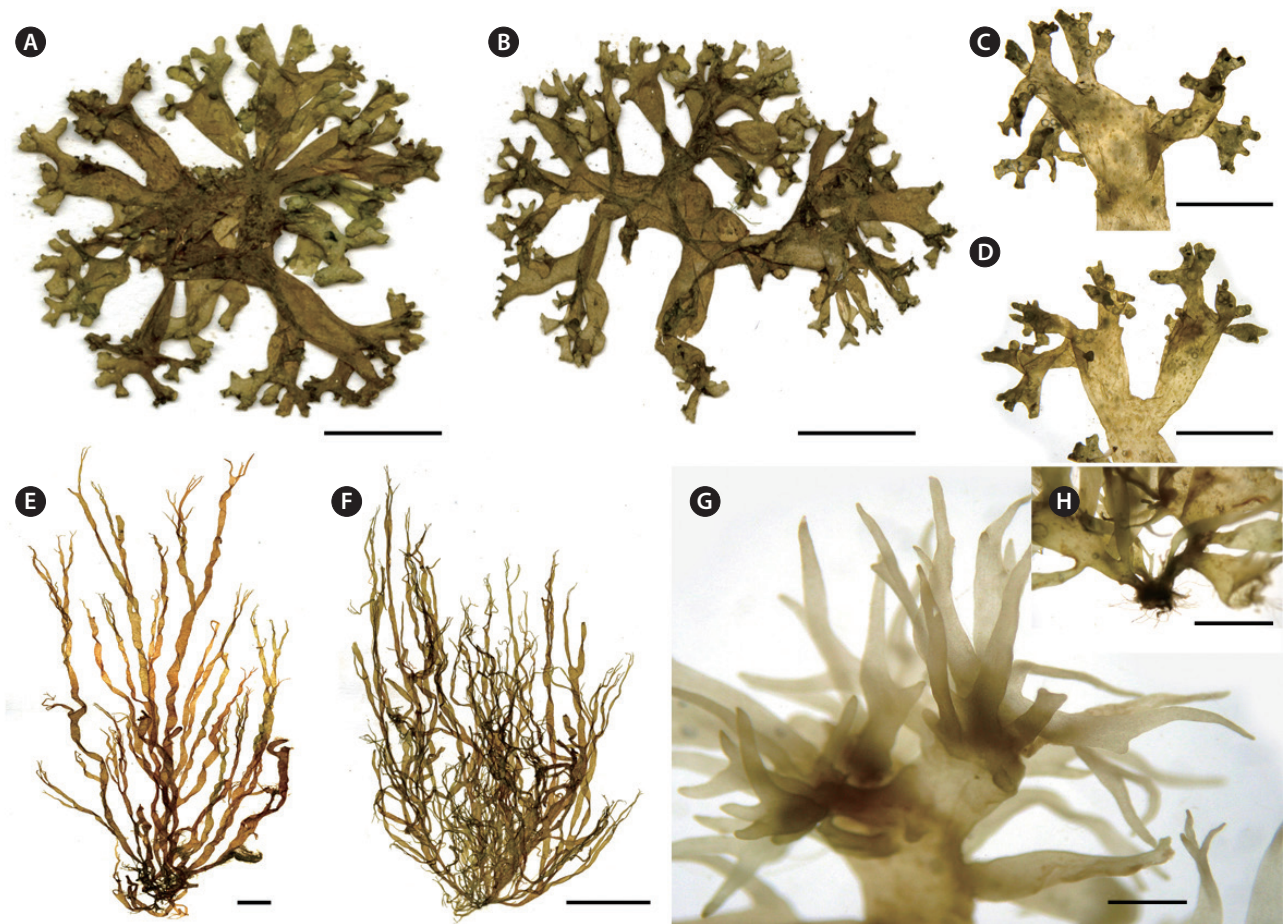


Fig. 3. Morphology of *Rosenvingea intricata* and *R. orientalis* from Vietnam. (A-D) morphology of *R. intricata*. (A & B) Herbarium specimens collected at Cam Ranh Bay, Nha Trang, Vietnam. (C & D) Subdichotomous to irregular branches. (E-H) Morphology of *R. orientalis*. (E & F) Herbarium specimens of *R. orientalis* collected at Cam Ranh Bay, Nha Trang, Vietnam. (G) Dichotomous branches in the upper thallus. (H) Holdfast. Scale bars represent: A, B, E & F, 1 cm; C & D, 500 μ m; G & H, 200 μ m.

Thalli of *R. orientalis* were up to 18 cm long with narrow (less than 2 mm in width), tubular to compressed fronds that are dichotomously branched in the upper thallus (Fig. 3E-H). The thalli were golden to light brown in color, with hollow axes, up to 2 mm in diameter. Branches were dichotomous to irregularly lobed, usually tapering at the base and apex, ends of branches nearly hair-like.

DISCUSSION

Our analyses of mitochondrial *cox3* and plastid *psaA* sequences clearly showed the occurrence of two genetically and morphologically distinct species of *Rosenvingea* from Nha Trang, Vietnam. We collected both species in Cam Ranh Bay, Nha Trang, Vietnam, and have assigned these species to *R. intricata* and *R. orientalis*. Morphologi-

cal comparison with other *Rosenvingea* species is given in Table 2.

R. intricata is the most common species in the genus reported in tropical to subtropical waters of the world (see Guiry and Guiry 2014). In *cox3* and *psaA* trees (excluding the Japanese taxon in the *cox3* tree due to the unavailability of the samples), *R. intricata* was separated into three different taxa. The first group was composed of specimens from Vietnam, Mexico, and Panama. The morphology of our plants is consistent with the description and illustration of *R. intricata* (Børgesen 1914, Earle 1969). We therefore recognized this taxon as *R. intricata* because the clade in our analyses included specimens collected from near the type locality in Veracruz, Mexico. Accordingly, our study confirmed the previous reports on the occurrence of *R. intricata* in Vietnam (Pham 1969, Nguyen et al. 1993) as well as Baja California in Mexico (Norris 2010)

Table 2. Morphological comparison of *Rosenvingea fastigiata* and *R. intricata* with similar species

	<i>R. fastigiata</i>	<i>R. intricata</i>	<i>R. antillarum</i>	<i>R. nhatrangensis</i>	<i>R. orientalis</i>	<i>R. sanctae-crucis</i>
Thallus shape	Terete dichotomous fronds that form either matted clumps or individual thalli	Low-growing clumps of cylindrical to compressed, crisp, subdichotomously to irregularly branched	Erect, composed of terete, internally hollow axes and branches, branching sparse and irregular 2-3 orders	Hollow, soft, thin-walled, flat, short-branched and lobed, terminally rounded	Pantropical with long and narrow tubular to compressed fronds, dichotomously branched in the upper thallus	Golden brown in color, cylindrical and irregularly branched with antler-like tips
Thallus size	Up to 12 cm long, 5 mm in width	Up to 30 cm long, 4-6 mm in width	Up to 55 cm long, 1-2 mm in width	Up to 4-6 cm tall, 10-15 mm in width	Up to 30 cm long, less than 2 mm in width	Up to 15 cm long, 2 mm in width
Cortical and medulla structure	2-3 cell layers	3-4 cell layers	4-6 cell layers	2-3 cell layers	2-3 cell layers	3-4 cell layers
Plurangia	Uni- to biseriata	Biseriate	Uni- to biseriata, 6-7 locules	Uni- to biseriata, 2-4 locules	Biseriate, 2-4 locules	Uni- to biseriata, 8-10 locules
Type locality	Sarawak, Malaysia	Veracruz, Gulf of Mexico, Mexico	Le Moule, Grade-Terre, Guadeloupe, French West Indies	Cua Bé near Truong Đông, Vietnam	Manilla, the Philippines	St. Croix, Virgin Islands
Geographical distribution	Asian-Pacific	Temperate to tropical waters	Gulf of California, Western Atlantic, Angola, South-west Asia	Vietnam, India, Papua New Guinea, Western Australia	Kenya in Africa, Florida in USA, Southeast Asia, Australia	Temperate waters
References	Børgesen (1914), Nguyen et al. (1993), Littler and Littler (2000)	Børgesen (1914), Abbott and Huisman (2004), Norris (2010), present study	Taylor (1955), Wynne (1997), Norris (2010)	Dawson (1954), Pham (1969)	Børgesen (1914), Earle (1969), Littler and Littler (2000), West et al. (2010), present study	Børgesen (1914), Littler and Littler (2000), Nelson and Wilcox (2010)

and Panama (Wysor and De Clerck 2003). The second taxon was the New Caledonia taxon (as GQ368280 in *cox3*, GQ368338 in *psaA*) that formed a sister to *R. intricata*. The pairwise divergence of *psaA* (54-55 bp, 3.9%) between the New Caledonian taxon and *R. intricata* is similar or higher than that between scytosiphonacean species (e.g., 2.2% between *Scytosiphon lomentaria* and *S. dotyi*) (Cho et al. 2006). The third taxon distinguished consisted of the Japanese specimens (DQ239784) and was distantly related to other taxa of *Rosenvingea*. These results reveal an urgent need for further molecular analysis of specimens currently assigned to *R. intricata* in various countries (see Guiry and Guiry 2014).

R. orientalis is distributed in subtropical to tropical waters of Kenya, Florida in USA, Southeast Asia, and Australasia (see Guiry and Guiry 2014). Its type locality is Manila, the Philippines, and its diagnostic characters are the tubular to compressed thalli, the tall size (up to 30 cm), narrow diameter of branches (less than 2 mm), and dichotomous branches (Børgesen 1914, Earle 1969, West et al. 2010). Following previous phycologists' opinions (Earle 1969, Littler and Littler 2000, Abbott and Huisman 2004, Wynne 2005), Nelson and Wilcox (2010) reported that *R. orientalis* may be conspecific with *R. santae-crucis* and the former has priority. Molecular analysis of type specimens or fresh collections of *R. santae-crucis* near the type locality are needed to resolve about the conspecificity of these taxa.

The absence of *R. nhatrangensis* in our collections despite our repeated samplings in the type locality, Nha Trang, Vietnam, suggests that there is an urgent need for an analysis of the type specimens of this and related taxa. *R. nhatrangensis* is distinguished by much inflated, lobed and short thalli with its wide diameter of branches (2.5-3.0 cm in lower part of erect thallus and 1.0-1.5 cm in the branches) (Dawson 1954). *R. fastigiata* var. *major* Reinbold reaches a branch diameter of 5 mm, and bears sori in rings around the hair groups. However, based on figures and description by Dawson (1954), Egerod (1974) suggested that *R. nhatrangensis* may be conspecific with *R. fastigiata* var. *major*. Kochang Archipelago, Thailand, the type locality of this variety is close to Nha Trang, Vietnam, the type locality of *R. nhatrangensis* (Reinbold 1901, Dawson 1954). Fresh collection of *R. fastigiata* var. *major* in the type locality is necessary to confirm their conspecificity.

This is the first study using mitochondrial *cox3* sequences to reveal the non-monophyly of the genus *Rosenvingea*. Our analyses showed that *Rosenvingea* that clustered with *Hydroclathrus* ssp., and *Chnoospora*

implexa. This topology was also reflected in the *psaA* tree with the inclusion of *Colpomenia sinuosa*. The non-monophyly of *Rosenvingea* revealed in the present study indicates the need for a reconsideration of the generic concept. However, based on the *cox3* and *psaA* trees, it is to date impossible to combine or rearrange these genera based on molecular data as none of the genera are monophyletic in the analyses. *Chnoospora*, *Colpomenia*, *Petalonia*, and *Scytosiphon* in the family Scytosiphonaceae have been confirmed to be non-monophyletic in *rbcL* and / or *psaA*, and *cox3* phylogenies (Kogame et al. 1999, Cho et al. 2006, Lee et al. 2014). As discussed by Kogame et al. (1999) and Cho et al. (2006), further investigations based on taxon-wide sampling, and employing other supplementary gene sequences, life histories, and ultrastructure of gametes, are urgently needed to clarify the relationships of all these currently non-monophyletic genera of the Scytosiphonaceae.

In conclusion, we confirmed the occurrence of *R. intricata* and *R. orientalis* from Nha Trang, Vietnam. Our study therefore reveals that both species are distributed from Vietnam to Mexico and / or Panama. Further collection and careful examination of specimens will probably extend the known distributions of both species to surrounding Vietnamese waters. Additional investigations are needed to confirm the relationships of *R. nhatrangensis* with *R. intricata* and *R. fastigiata* var. *major*. The finding of cryptic species within *R. intricata* highlights the fact that the number of *Rosenvingea* species in the world inventory will increase with additional collections.

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