A review on the distribution records of mangrove-associated heterocytous cyanobacteria: an update

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Abstract:

Microorganisms associated with mangrove habitats have an important role in this ecosystem, contributing significantly to its productivity and ecosystem maintenance. Studies on the distribution of mangroves inhabiting cyanobacterial diversity are scarce and meagre. This study aims to record the occurrence and geographic distribution of the heterocytous cyanobacteria in mangrove environments during 43 years of research carried out by different countries in the world. We consulted 33 publications (national and international journals and books published from 1977 to 2020). There are a total of 70 heterocytous cyanobacterial species. The dominant family was Nostocaceae with 27 species, followed by Calotrichaceae with 12 species, Rivulariaceae and Scytonemataceae with 10 species each, Aphanizomenonaceae with 5 species, Hapalosiphonaceae with 2 species, Chlorogloeopsidaceae, Heteroscytonemataceae, Microchaetaceae and Tolypothrichaceae with one species each. This study will be a contribution to our knowledge of cyanobacterial biodiversity in mangrove ecosystems and generate data for future taxonomic, ecological and biogeographic studies.

Keywords: Cyanobacteria, heterocytous, mangrove environment, biodiversity.

Introduction

Cyanobacteria are the most ancestral lineage responsible for the generation of an oxygen-rich atmosphere that originated before 3.0 Ga **(Schirrmeister *et al.*, 2015).** Taxonomic classification of cyanobacteria is the only method for understanding their diversity and diversification processes **(Komarek, 2013).** The modern taxonomic classification of cyanobacteria must be continually revised to

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incorporate data resulting from the polyphasic evaluation of cyanobacterial diversity. **Komarek and Anagnostidis (1998)** classified cyanobacteria into 14 families based on the presence or absence of false branching, true branching and heterocytes, for discussion, they used the terms ‘heterocytes’ and ‘hormogonia’ rather than ‘heterocysts’ and ‘hormogones’, as recommended by the International Association for Cyanophyte Research (IAC) **(Mollenhauer *et al.*, 1994).**

Cyanobacteria play a pivotal role in mangrove ecosystems as they are the primary producers of organic carbon and nitrogen. Many cyanobacterial species provide nitrogen by biological nitrogen fixation and as a significant group within the diazotrophic guild, contribute to the availability of nitrogen in the system **(Toledo *et al.*, 1995).** Studies on the nitrogen-fixing capability of cyanobacteria in mangroves have been carried out in a few regions of the world **(Ramachandran and Venugopalan, 1987; Kyaruzi *et al.*, 2003; Boopathi, 2011).** Some studies focused on cyanobacteria that grow on the surface of mangrove tree trunks, aerial roots, pneumatophores and leaves and their contribution to biological nitrogen-fixing capability has been assessed **(Mann and Steinke, 2003; Lugomela and Bergman, 2002).**

Data on mangrove-associated cyanobacteria are scarce throughout the world. Research on this topic is particularly rare and is restricted to certain regions **(Lambert *et al.*, 1987).** To the best of our knowledge, the first published literature appeared in 1977 **(Potts and Whitton, 1977)** who reported the occurrence of heterocytous mangrove-associated cyanobacteria *Calothrix crustacea* Thuret ex Bornet & Flahault 1886 (Current name: *Scytonematopsis crustacea* (Thuret ex Bornet & Flahault) Kovacik & Komarek 1988) from the intertidal zone of the lagoon shores of West Island, Aldabra. The general aim of this work is to provide an updated revision of the diversity and distribution of previously recorded cyanobacteria in mangrove ecosystems. The need for conducting surveys to fulfil research gaps in this field, including the global distribution pattern of mangrove-associated cyanobacteria, can be used as a reliable database for future major research studies in this field.

Materials and Methods

The data on heterocytous cyanobacteria associated with mangroves has been compiled solely from published works of literature from 1977-2020. We used 33 research papers and books published nationally and internationally to create a catalogue of cyanobacterial species and the articles in which they are cited. Cyanobacteria can be found in diverse habitats, including epipsammic/edaphic, epizoic, epiphytic, planktic, benthic, and epilithic forms, all of which are common in mangrove ecosystems. The occurrence of cyanobacterial species may not be explicitly indicated in some publications; instead, such species are included under the category 'mangrove environment'. Different methods for collecting cyanobacteria were discussed in the original research literature, which is cited in this study.

The list is exclusively based on published works of literature. We considered only published works that referenced cyanobacteria at the species level of identification. Names of taxa are given with the proper author citation. Species are classified according to their respective families. The species are classified based on the current classification system proposed by **Komarek *et al.* (2014)** and **Hauer and Komarek (2021)** and the entities of the taxonomically accepted species are verified by **Guiry and Guiry (2021).** When a specific or infraspecific taxon is recorded under a synonym if cited, it is represented under the currently accepted names.

Results and Discussion

This study aims to compile a catalogue of mangroves inhabiting cyanobacteria and to revise and update the nomenclature to reflect current taxonomically accepted names for the previously documented species. From the 33 research articles and books published nationally and internationally from 1977 to 2020, we considered cyanobacteria to have species-level identification. The results indicated 70 heterocytous cyanobacterial species in which 47 are from mangrove environments, 17 epiphytic, 11 planktic, 12 epilithic, 5 epipsammic/edaphic, 2

benthic, 1 epiphyllic and 1 epizoic, while 4 species co-occur among mangrove environments, epipsammic and epiphytic, 2 species co-occur in mangrove environments, epilithic and epiphytic, 4 species co-occur in both epiphytic and mangrove environments, 4 species co-occur in both planktic and mangrove environments, 1 species co-occurs in both epilithic and epizoic, 1 species co-occurs in both epilithic and mangrove environments, 1 species co-occurs in both planktic and benthic environments (Table 1). From this documentation study, the family Nostocaceae was the dominant family with 27 taxa, followed by Calotrichaceae had 12 taxa, Rivulariaceae and Scytonemataceae had 10 taxa each, Aphanizomenonaceae had 5 taxa, Hapalosiphonaceae had 2 taxa and Chlorogleopsidaceae, Heteroscytonemataceae, Microchaetaceae and Tolypothrichaceae had one species each (Figure 1).

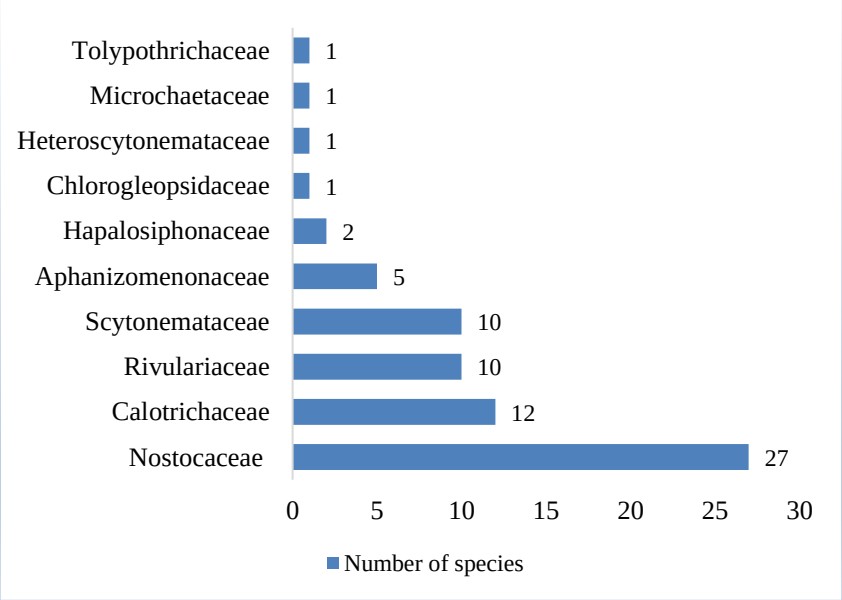

Figure 1: Graphical position and number of species from the mangrove-associated cyanobacteria according to family.

Table 1: Occurrence of cyanobacterial species from the mangrove environments, habitat, country/provinces and their respective citations are provided. The updated species name was based on Algaebase; (=) symbol indicates the species synonyms if cited in the referred work.

List of cyanobacterial species	Habitat	Country/ Province	References
Nostocales - Aphanizomenonaceae			
Anabaenopsis arnoldii Aptekar 1926	Planktic	India	**Sen and Naskar, 2003**
Dolichospermum flosaquae (Brebisson ex Bornet & Flahault) P.Wacklin, L.Hoffmann & J.Komarek 2009 (=) *Anabaena flosaquae* Brebisson ex Bornet & Flauhault 1886	Mangrove environment	India	**Barman *et al.*, 2015**
Dolichospermum spiroides (Klebhan) Wacklin, L.Hoffmann & Komarek 2009 (=) *Anabaena spiroides* Klebahn 1895	Mangrove environment	India	**Bhuvaneshwari and Muruganandam, 2016**
			Priya *et al.*, 2019
Nodularia spumigena Mertens ex Bornet & Flahault 1888	Mangrove environment	India	**Ramamurthy and Abhinand, 2016**
	Mangrove Swamps	Saudi Arabia	**Hussain and Khoja, 1993**
	Mangrove environment	India	**Sudha, 2005**
	Mangrove environment	India	**Sudha *et al.*, 2007**
	Epipsammic	Nigeria	**Essien *et al.*, 2008**
	Epiphytic	India	**Nedumaran *et al.*, 2008**
Nodularia spumigena var. *major* Bornet & Flahault 1886	Mangrove Swamps	Saudi Arabia	**Hussain and Khoja, 1993**
Nostocales – Calotrichaceae			
Calothrix aeruginosa Woronichin 1923	Epiphytic	Australia	**Huisman *et al.*, 2015**
	Epiphytic	Egypt	**Potts, 1980**
Calothrix bharadwajae G.De Toni 1939	Mangrove environment	India	**Silambarasan *et al.*, 2012**

Calothrix breviarticulata West & G.S.West 1897	Mangrove environment	Saudi Arabia	**Mohammed and Al-Shehri, 2015**
Calothrix brevissima G.S.West 1907	Epiphytic, Edaphic	Pakistan	**Bano and Siddiqui, 2007**
	Mangrove environment	India	**Silambarasan *et al.*, 2012**
Calothrix castellii Bornet & Flahault 1886	Epiphytic	India	**Boopathi, 2011**
Calothrix clavata G.S.West 1914	Mangrove environment	India	**Barman *et al.*, 2015**
Calothrix confervicola C.Agardh ex Bornet & Flahault 1886	Micrbial mat, Mangrove Swamps	Saudi Arabia	**Hussain and Khoja,1993**
Calothrix contarenii Bornet & Flahault 1886	Epipsammic	Aldabra Islands	**Potts and Whitton, 1980**
	Epiphytic	Africa	**Lambert *et al.*, 1989**
	Epiphytic	Africa	**Steinke et al., 2003**
	Mangrove environment	India	**Sudha, 2005**
	Mangrove environment	India	**Sudha et al., 2007**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
	Mangrove environment	India	**Bhuvaneshwari and Muruganandam, 2016**
	Mangrove environment	India	**Priya *et al.*, 2019**
Calothrix fusca Bornet & Flahault 1886	Epilithic	Pakistan	**Bano and Siddiqui, 2007**
Calothrix ghosei Bharadwaja 1935	Mangrove environment	India	**Bhuvaneshwari and Muruganandam, 2016**
			Priya et al., 2019
Calothrix pulvinata C.Agardh ex Bornet & Flahault 1886	Mangrove Swamps, Epilithic	Saudi Arabia	**Hussain and Khoja, 1993**
	Epiphytic	India	**Nedumaran *et al.*, 2008**

Calothrix scopulorum C.Agardh ex Bornet & Flahault 1886	Epilithic	Egypt	**Potts, 1980**
	Epiphytic	Africa	**Lambert *et al.*, 1989**
	Epiphytic	Africa	**Silva, 1991**
	Microbial mat, Mangrove Swamps	Saudi Arabia	**Hussain and Khoja, 1993**
	Epiphytic	Africa	**Steinke *et al.*, 2003**
	Mangrove environment	India	**Sudha, 2005**
	Mangrove environment	India	**Sudha *et al.*, 2007**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
	Mangrove environment	Saudi Arabia	**Mohammed and Al-Shehri, 2015**
Nostocales – Chlorogloeopsidaceae			
Chlorogloea fritschii A.K.Mitra 1950; Nostoc fritschii (Mitra) Schwabe & El Ayouty 1966	Epiphytic	Pakistan	**Bano and Siddiqui, 2007**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
	Mangrove environment	India	**Joseph and Saramma, 2016**
Nostocales – Hapalosiphonaceae			
Hapalosiphon welwitschii West & G.S.West 1897	Mangrove environment	India	**Sudha, 2005**
	Mangrove environment	India	**Sudha *et al.*, 2007**
	Mangrove environment	India	**Ramamurthy and Abhinand, 2016**
Mastigocoleus testarum Lagerheim ex Bornet & Flahault 1886	Epilithic	Egypt	**Potts, 1980**
	Epizoic	India	**Sen and Naskar, 2003**

Nostocales – Heteroscytonemataceae			
Heteroscytonema crispum (Bornet ex De Toni) G.B.McGregor & Sendall 2018 (=) *Scytonema crispum* Bornet ex De Toni 1907	Epiphytic	Australia	**Huisman *et al.*, 2015**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
Nostocales – Microchaetaceae			
Microchaete grisea Thuret ex Bornet & Flahault 1886	Epilithic	Pakistan	**Bano and Siddiqui, 2007**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
Nostocales – Nostocaceae			
Anabaena iyengarii Bharadwaja 1935	Mangrove environment	India	**Silambarasan *et al.*, 2012**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
Anabaena orientalis S.C.Dixit 1936	Mangrove environment	India	**Bhuvaneshwari and Muruganandam, 2016**
	Mangrove environment	India	**Priya *et al.*, 2019**
Anabaena oscillarioides Bory ex Bornet & Flahault 1886	Microbial mat	Saudi Arabia	**Hussain and Khoja, 1993**
Anabaena sphaerica Bornet & Flahault 1886	Mangrove environment	India	**Silambarasan et al., 2012**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
	Mangrove environment	India	**Barman *et al.*, 2015**
	Mangrove environment	Saudi Arabia	**Mohammed and Al-Shehri, 2015**
	Mangrove environment	India	**Ramamurthy and Abhinand, 2016**
Anabaena torulosa Lagerheim ex Bornet & Flahault 1886	Mangrove environment	India	**Silambarasan *et al.*, 2012**
Cylindrospermum majus Kutzing ex Bornet & Flahault 1888	Planktic	India	**Nedumaran *et al.*, 2008**

Desmonostoc muscorum (C.Agardh ex Bornet & Flahault) Hrouzek & Ventura 2013 (=) *Nostoc muscorum* C.Agardh ex Bornet & Flahault 1888	Planktic, Benthic	India	**Ram and Shamina, 2015**
	Mangrove environment	India	**Ramamurthy and Abhinand, 2016**
	Mangrove environment	India	**Ram and Shamina, 2017**
Hydrocoryne enteromorphoides (Grunow ex Bornet & Flahault) Umezaki & M.Watanabe 1994	Mangrove Swamps, Pelagic	Saudi Arabia	**Hussain and Khoja, 1993**
Nostoc carneum C.Agardh ex Bornet & Flahault 1886	Mangrove environment	India	**Barman *et al.*, 2015**
Nostoc commune Vaucher ex Bornet & Flahault 1888	Mangrove environment	India	**Barman *et al.*, 2015**
Nostoc ellipsosporum Rabenhorst ex Bornet & Flahault 1886	Mangrove environment	India	**Barman *et al.*, 2015**
	Mangrove environment	India	**Ram and Shamina, 2017**
Nostoc linckia Bornet ex Bornet & Flahault 1886 (=) *Nostoc piscinale* Kutzing ex Bornet & Flahault 1886	Epiphytic	India	**Sen and Naskar, 2003**
	Mangrove environment	India	**Bhuvaneshwari and Muruganandam, 2016**
	Mangrove environment	India	**Priya *et al.*, 2019**
Nostoc microscopicum Carmichael ex Bornet & Flahault 1886	Mangrove environment	India	**Shamina *et al.*, 2014**
	Mangrove environment	India	**Ram and Shamina, 2017**
Nostoc oryzae (F.E.Fritsch) J.Komarek & K.Anagnostidis 1989 (=) *Anabaena oryzae* F.E.Fritsch 1949	Epiphytic	India	**Boopathi, 2011**
Nostoc paludosum Kutzing ex Bornet & Flahault 1886	Mangrove environment	India	**Nedumaran *et al.*, 2008**
	Mangrove environment	India	**Ram and Shamina, 2017**
Nostoc passerinianum Bornet & Thuret ex Bornet & Flahault 1886	Benthic	India	**Ram and Shamina, 2015**
	Mangrove environment	India	**Ram and Shamina, 2017**
Nostoc punctiforme Hariot 1891	Planktic	India	**Sen and Naskar, 2003**

Raphidiopsis curvata Fritsch & M.F.Rich 1930	Planktic	India	**Sen and Naskar, 2003**
Raphidiopsis indica R.N.Singh 1942	Planktic	India	**Sen and Naskar, 2003**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
Richelia intracellularis J.Schmidt 1901	Mangrove environment	India	**Ramamurthy and Abhinand, 2016**
Trichormus doliolum (Bharadwaja) Komarek & Anagnostidis 1989 (=) *Anabaena doliolum* Bharadwaja 1935	Planktic	India	**Sen and Naskar, 2003**
Trichormus khannae (Skuja) Komarek & Anagnostidis 1989 (=) *Anabaena khannae* Skuja 1949	Mangrove environment	India	**Joseph and Saramma, 2016**
Trichormus anomalus (F.E.Fritsch) Komarek & Anagnostidis 1989 (=) *Anabaena anomala* F.E.Fritsch 1949	Planktic	India	**Sen and Naskar, 2003**
	Rock pool water, Coastal waters of mangrove waters	Pakistan	**Bano and Siddiqui, 2007**
Trichormus ellipsosporus (F.E.Fritsch) Komarek & Anagnostidis 1989 (=) *Anabaena variabilis* var. *ellipsospora* F.E. Fritsch 1949	Mangrove environment	India	**Silambarasan *et al.*, 2012**
Trichormus gelatinicola (Ghose) Komarek & Anagnostidis 1989 (=) *Anabaena gelatinicola Ghose 1924*	Planktic	India	**Sen and Naskar, 2003**
Trichormus variabilis (Kutzing ex Bornet & Flahault) Komarek & Anagnostidis 1989 (=) *Anabaena variabilis* Kutzing ex Bornet & Flahault 1886	Mangrove Swamps	Saudi Arabia	**Hussain and Khoja, 1993**
	Planktic	India	**Nedumaran *et al.*, 2008**
	Mangrove environment	India	**Barman *et al.*, 2015**
Wollea ambigua (C.B.Rao) R.Y.Singh 1942 (=) *Anabaena ambigua* C.B.Rao 1937	Planktic	India	**Kannan and Vasantha, 1992**
	Planktic	India	**Nedumaran *et al.*, 2008**

Nostocales – Rivulariaceae			
Dichothrix baueriana Bornet & Flahault 1886	Mangrove environment	India	**Silambarasan *et al.*, 2012**
	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
	Mangrove environment	India	**Ramamurthy and Abhinand, 2016**
Dichothrix penicillata Zanardini ex Bornet & Flahault 1886	Mangrove Swamps, Epilithic	Saudi Arabia	**Hussain and Khoja, 1993**
Dichothrix utahensis Tilden 1898	Epiphytic	Australia	**Huisman *et al.*, 2015**
Phyllonema aviceniicola Alvarenga, Rigonato, Branco, Melo & M.F.Fiore 2016	Epiphyllic	Brazil	**Alvarenga *et al.*, 2016**
Kyrtuthrix dalmatica Ercegovic 1929	Epilithic	Egypt	**Potts, 1980**
Kyrtuthrix maculans (Gomont) I.Umezaki 1958	Epilithic	Egypt	**Potts, 1980**
Gardnerula corymbosa De Toni 1936	Epipsammic	Egypt	**Potts, 1980**
Rivularia atra Roth ex Bornet & Flahault 1886	Epiphytic	Australia	**Beanland and Woelkerling, 1983**
	Epiphytic	Australia	**Huisman *et al.*, 2015**
Rivularia bullata Berkeley ex Bornet & Flahault 1886	Epiphytic	Africa	**Lambert *et al.*, 1989**
	Epiphytic	Africa	**Steinke *et al.*, 2003**
Rivularia polyotis Roth ex Bornet & Flahault 1886	Epiphytic	Australia	**Beanland and Woelkerling, 1983**
	Mangrove Swamps	Saudi Arabia	**Hussain and Khoja, 1993**
	Epiphytic	Egypt	**Gab-Alla, 2000**
Nostocales – Scytonemataceae			
Scytonema hofmanii C.Agardh ex Bornet & Flahault 1886	Epiphytic	Africa	**Lambert *et al.*, 1989**
	Epilithic	Saudi Arabia	**Hussain and Khoja, 1993**
	Epilithic	India	**Sen and Naskar, 2003**
	Epiphytic	Africa	**Steinke *et al.*, 2003**
Scytonema arcangelii Bornet & Flahault 1886	Mangrove environment	Brazil	**Nogueira and Ferrieira-Correia, 2001**

Scytonema bohneri Schmidle 1901	mangrove environment	India	**Barman *et al.*, 2015**
	Planktic	India	**Ram and Shamina, 2015**
	Mangrove environment	India	**Ram and Shamina, 2017**
Scytonema chiastum Geitler 1925	mangrove environment	India	**Silambarasan *et al.*, 2012**
Scytonema insulare C.L.Sant'Anna 1988	Mangrove environment	Brazil	**Nogueira and Ferrieira-Correia, 2001**
Scytonema leptobasis S.L.Ghose 1931	Planktic	India	**Ram and Shamina, 2015**
	Mangrove environment	India	**Ram and Shamina, 2017**
Scytonema saleyeriense Weber Bosse 1913	Mangrove Swamps	Saudi Arabia	**Hussain and Khoja, 1993**
Scytonema varium Kutzing ex Bornet & Flahault 1886	Mangrove environment	India	**Silambarasan *et al.*, 2012**
Scytonematopsis crustacea (Thuret ex Bornet & Flahault) Kovacik & Komarek 1988 (=) *Calothrix crustacea* Thuret ex Bornet & Flahault 1886	Mangrove environment	India	**Sakthivel and Kathiresan, 2013**
	Mangrove environment	Saudi Arabia	**Mohammed and Al-Shehri, 2015**
	Epipsammic	Aldabra	**Potts and Whitton, 1977**
	Epiphytic	Egypt	**Potts, 1980**
	Epipsammic	Aldabra Islands	**Potts and Whitton, 1980**
	Epiphytic	Epiphytic	**Silva, 1991**
	Mangrove Swamps, Epilithic	Saudi Arabia	**Hussain and Khoja,1993**
	Mangrove environment	India	**Dhargalkar, 1994**
	Epiphytic	Pakistan	**Saifullah *et al.*, 1997**
	Epiphytic	India	**Sen and Naskar, 2003**
	Mangrove environment	India	**Sudha, 2005**
	Mangrove environment	India	**Sudha *et al.*, 2007**

Scytonematopsis pilosa (Harvey ex Bornet & Flahault) I.Umezaki & M.Watanabe 1994 (=) *Calothrix pilosa* Harvey ex Bornet & Flahault 1886	Epilithic	Egypt	**Potts, 1980**
Nostocales – Tolypothricaceae			
Tolypothrix tenuis Kutzing ex Bornet & Flahault 1886	Mangrove environment	India	**Joseph and Saramma, 2016**

While compiling the elaborate list of cyanobacterial diversity with a special focus on mangrove environments, we consider only the specimen taxonomically identified up to the species level. It is noticed that research on mangrove-associated cyanobacterial diversity has become more focused since 1990 and a significant rise in biodiversity research has been recorded over recent decades. However, no taxonomic studies have been published as of 2020. There is a total lack of knowledge on the taxonomy of mangrove-associated cyanobacteria and are very scarce and meagre. As a result, the diversity and ecological importance of these habitats are highly neglected.

Based on existing data, it is clear that cyanobacterial floristic surveys should be carried out in diverse biotopes of tropical regions that are still to be explored as they can greatly contribute to our understanding of geographic distribution as well as relevant information for the taxonomy of these organisms. Recent developments in polyphasic approaches will help to explore a good percentage of the cyanobacterial community that can be exploited for the benefit of mankind.

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