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 Calothrichaceae 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
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 epiphylic 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 & Flahault 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 | Silambasarasan 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 | Silambaresan 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, 1989 |
| | 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 Murugananandam, 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 Murugananandam, 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 |
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| Species                          | Type     | Location          | Authors                  |
|----------------------------------|----------|-------------------|--------------------------|
| 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      |
|                                  |          | India             | Sudha, 2005               |
|                                  |          | India             | Sudha et al., 2007        |
|                                  |          | India             | Sakthivel and Kathiresan, 2013 |
|                                  |          | Saudi Arabia      | Mohammed and Al-Shehri, 2015 |
| Nostoccales – Chlorogloeopsidaceae |          | Epiphytic         | Pakistan                 |
| Chlorogloea fritschii A.K.Mitra 1950; Nostoc fritschii (Mitra) Schwabe & El Ayouty 1966 |          | Pakistan          | Bano and Siddiqui, 2007   |
|                                  |          | India             | Sakthivel and Kathiresan, 2013 |
|                                  |          | India             | Joseph and Saramma, 2016  |
| Nostoccales – Hapalosiphonaceae  |          |          | Sudha, 2005              |
| Hapalosiphon welwitschii West & G.S.West 1897 | 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 & Flahaut 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 & Flahaut 1886 | Microbial mat | Saudi Arabia | Hussain and Khoja, 1993 |
| *Anabaena sphaerica* Bornet & Flahaut 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 & Flahaut 1886 | Mangrove environment | India | Silambarasan *et al.*, 2012 |

| Cylindrospermum majus* Kutzing ex Bornet & Flahaut 1888 | Planktic | India | Nedumaran *et al.*, 2008 |
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| Species | Synonym | Environment | Location | Reference |
|---------|---------|-------------|----------|-----------|
| *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 |
| *Nostoc commure* Vaucher ex Bornet & Flahault 1888 | | Mangrove environment | India | Ramamurthy and Abhinand, 2016 |
| *Nostoc ellipsosporum* Rabenhorst ex Bornet & Flahault 1886 | | Mangrove environment | India | Ram and Shamina, 2017 |
| *Nostoc carneum* C.Agardh ex Bornet & Flahault 1886 | | Mangrove environment | India | Ram and Shamina, 2017 |
| *Nostoc linekia* Bornet ex Bornet & Flahault 1886 | (=) *Nostoc piscinale* Kutzing ex Bornet & Flahault 1886 | Epiphytic | India | Hussain and Khoja, 1993 |
| *Nostoc microscopticum* Carmichael ex Bornet & Flahault 1886 | | Mangrove environment | India | Barman et al., 2015 |
| *Nostoc oryzae* (F.E.Fritsch) J.Komarek & K.Anagnostidis 1989 | (=) *Anabaena oryzae* F.E.Fritsch 1949 | | | Boopathi, 2011 |
| *Nostoc paludosum* Kutzing ex Bornet & Flahault 1886 | | Mangrove environment | India | Nedumaran et al., 2008 |
| *Nostoc passerinianum* Bornet & Thuret ex Bornet et Flahault 1886 | | Benthic | India | Ram and Shamina, 2015 |
| *Nostoc punctiforme* Hariot 1891 | | Planktic | India | Sen and Naskar, 2003 |
| Species                                      | Environment       | Location                  | Authors                          |
|----------------------------------------------|-------------------|---------------------------|----------------------------------|
| *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 anomalus* 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 & Flahaut) Komarek & Anagnostidis 1989 (= *Anabaena variabilis* Kutzing ex Bornet & Flahaut 1886) | Mangrove Swamps  | Saudi Arabia              | Hussain and Khoja, 1993          |
|                                              | Planktic          | India                     | Nedumaran et al., 2008           |
|                                              | Mangrove environment | India                     | Barman et al., 2015              |
| *Wollea ambiguа* (C.B.Rao) R.Y.Singh 1942 (= *Anabaena ambiguа* C.B.Rao 1937) | Planktic          | India                     | Kannan and Vasantha, 1992        |

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| 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 environment | India |  |
|  | 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 | Epiphylic | Brazil | *Alvarenga et al., 2016* |
| *Kyrtuthrix dalmatica* Eregeovic 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-Ala, 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 Ferreira-Correia, 2001* |

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| Species                          | Environment | Location       | Reference                        |
|---------------------------------|-------------|----------------|----------------------------------|
| *Scytonema bohneri* Schmidle 1901 | mangrove    | India          | Barman *et al.*, 2015            |
|                                  | Planktic    | India          | Ram and Shamina, 2015            |
|                                  | Mangrove    | India          | Ram and Shamina, 2017            |
| *Scytonema chiastum* Geitler 1925 | mangrove    | India          | Silambarasan *et al.*, 2012      |
| *Scytonema insulare* C.L. Sant’Anna 1988 | Mangrove  | Brazil         | Nogueira and Ferreira-Correia, 2001 |
| *Scytonema leptobasis* S.L. Ghose 1931 | Planktic    | India          | Ram and Shamina, 2015            |
|                                  | Mangrove    | India          | Ram and Shamina, 2017            |
| *Scytonema saleyeriense* Weber Bosse 1913 | Mangrove  | Saudi Arabia   | Hussain and Khoja, 1993          |
| *Scytonema varium* Kutzing ex Bornet & Flahault 1886 | Mangrove  | India          | Silambarasan *et al.*, 2012      |
| *Scytonematopsis crustacea* (Thuret ex Bornet & Flahault) Kovacik & Komarek 1988 (= *Calothrix crustacea* Thuret ex Bornet & Flahault 1886) | Mangrove  | India          | Sakthivel and Kathiresan, 2013   |
|                                  | Mangrove    | 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    | Saudi Arabia   | Hussain and Khoja, 1993          |
|                                  | Swamps,     |                | Dharagkar, 1994                  |
|                                  | Epilithic   |                |                                  |
|                                  | Epiphytic   | Pakistan       | Saifullah *et al.*, 1997         |
|                                  | Epiphytic   | India          | Sen and Naskar, 2003             |
|                                  | Mangrove    | India          | Sudha, 2005                      |
|                                  | environment |                |                                  |
|                                  | Mangrove    | India          | Sudha *et al.*, 2007             |
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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