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Lithophytic Cyanobacteria on Indian Stone Temples and Monuments

Rashmi Kala and V. D. Pandey*

Department of Botany, Pt. L.M.S. Govt. Post-Graduate College, Rishikesh, Uttarakhand, India

**Corresponding author*

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A B S T R A C T

India is rich in lithic (stone-built) temples and monuments which epitomize our rich cultural heritage and contribute significantly to the tourism and economy of the country. The light-exposed surfaces of temples and monuments are readily colonized and inhabited by various species, belonging to different genera, of lithophytic (lithobiontic) cyanobacteria (blue-green algae). Lithophytic cyanobacteria possess remarkable adaptability and tolerance to various abiotic stresses, such as desiccation, high light intensity, high levels of solar UV radiation and high temperature which they often encounter on exposed rock surfaces and external walls of lithic temples, monuments and buildings. They are primary colonizers of nutrient-poor lithic substrata. Lithophytic cyanobacteria can grow both as epiliths and endoliths. They comprise major component of sub-aerial biofilms or crusts on exposed surfaces.The colonization and growth of lithophytic cyanobacteria can affect stone-built temples, monuments and buildings directly or indirectly in various ways, ultimately resulting in their biodeterioration that is manifested as both aesthetic and structural damage. Biodeterioration of stone-built monuments and buildings is a serious problem globally. The article provides an overview of the occurrence and diversity of lithophytic cyanobacteria on Indian stone-built temples and monuments and their potential effects.

Introduction

India is rich in lithic (stone-built) temples, monuments and heritage structures which epitomize our rich cultural heritage and contribute significantly to the tourism and economy of the country. Built of different constructional materials such as stones (e.g. marbles, sandstone, limestone and granite), bricks, concrete and mortars, they exhibit varying sculpture, style and decoration. They were built during different periods of time in history. They attract tourists, visitors and devotees in varying number throughout the year. Biodeterioration of lithic monuments, architectural buildings and heritage structures due to the colonization, growth and activities of various microorganisms, including cyanobacteria, resulting in their both aesthetic and structural damage, constitutes a major and serious problem globally (Warscheid and Braams, 2000; Crispim and Gaylarde, 2005; Crispim *et al.,* 2006; Scheerer *et al.,* 2009; Macedo *et al.,* 2009).

Cyanobacteria (blue-green algae) are a fascinating and remarkably diverse group of photoautotrophic organisms with prokaryotic cellular structure and oxygenic photosynthesis (Carr and Whitton, 1982; Castenholz and Waterbury, 1989). Possessing tremendous adaptability to varying environmental conditions, they are widely distributed organisms inhabiting diverse aquatic and terrestrial habitats in nature (Tandaeu de Marsac and Houmard, 1993; Whitton and Potts, 2000; Gaysina *et al.,* 2019). Both ecologically and economically, cyanobacteria are recognized as an important group of organisms. In ecosystem, they play prominent role in carbon, oxygen and nitrogen cycling (Tomitani *et al.,* 2006; Waterbury *et al.,* 1979). They contribute significantly to the primary production of various ecosystems, particularly freshwater and marine ecosystems, and account for about 30% of global primary production (Hagemann, 2011).

As lithophytes or lithobionts (rock-dwelling organisms), cyanobacteria colonize and inhabit a variety of lithic habitats, including natural rocks/stones as well as buildings, monuments and heritage structures constructed of stones, bricks, concrete and mortar (Büdel, 1999; Crispim *et al.,* 2006; Pandey, 2013). The nature (lithotype) and properties of stone as well as environmental factors, such as temperature, relative humidity, rainfall, wind and light are known to influence the colonization and growth of cyanobacteria and other organisms on a lithic substratum (Guillitte, 1995; Guillitte and Dreesen, 1995; Gaylarde *et al.,* 2003; Gaylarde, 2020; Miller *et al.,* 2012).

Stress tolerance in lithophytic cyanobacteria

Exposed lithic habitats, such as natural rocks/stones and exteriors of temples, monuments and buildings are unique habitats with challenging and limiting growth conditions for the colonization, growth and survival of microorganisms, including cyanobacteria. Cyanobacteria growing in these habitats experience frequentand prolonged desiccation (water stress), nutrient scarcity, high and variable temperature, high irradiance (light intensity) combined with high levels of ultraviolet (UV) radiation (Büdel, 1999). These pose multiple abiotic stresses for the growth and survival of cyanobacteria. Moreover, many abiotic stresses act as factors to induce oxidative stress in the organisms. Cyanobacteria are known to possess tolerance or protective mechanisms against various abiotic stresses, such as desiccation (Dadheech, 2010; Potts, 1994, 1999), high light intensity (Donkor and Häder, 1995; Lakatos *et al.,* 2001), UV- radiation (Ehling-Schulz and Scherer, 1999; Quesada and Vincent, 1997; Groniger *et al.,* 2000), high temperature (Adhikary, 2003; Hossain and Nakamoto, 2002; Singh *et al.,* 2005), oxidative stress (Hossain and Nakamoto, 2003; Qiu *et al.,* 2003; Latifi *et al.,* 2009; Richa and Sinha, 2011).

The tolerance of cyanobacteria to various abiotic stresses constitutes their eco-physiological adaptation or survival strategies for growth and survival on exposed surfaces of rocks and stone-built monuments and buildings. Tolerance against desiccation is attributed to the production of mucilaginous extracellular polymeric substances (EPS) by cyanobacteria (De Philippis and Vincenzini, 1998; Rossi and De Philippis, 2015). Intracellular accumulation of compatible organic solutes, viz. proline, sucrose and trehalose are also known to protect cyanobacteria against desiccation (Lin and Wu, 2014; Chaneva *et al.,* 2011; Hershkovitz *et al.,* 1991; Sakamoto *et al.,* 2009).

Scytonemin and mycosporine-like amino acids (MAAs) are UV-photoprotective compounds/pigments reported in many cyanobacteria, including those growing on exposed surfaces of monuments and buildings (Garcia-Pichel and Castenholz, 1991, 1993; Ehling-Schulz and Scherer, 1999; Groniger *et al.,* 2000; Roy *et al.,* 1997; Pattanaik and Adhikary, 2001; Adhikary and Sahu, 1998). Scytonemin is a yellow-brownish, lipid-soluble pigment located in the extracellular sheaths of many cyanobacteria whereas MAAs are intracellular water-soluble substances.The role of carotenoids in photoprotection against high light intensities is known in all photosynthetic organisms, including cyanobacteria (Hirschberg and Chamovitz, 1994; Lakatos *et al.,* 2001).

Classification of lithophytic cyanobacteria

Rocks provide unusual habitats for the growth of various organisms, including cyanobacteria. The rock-dwelling organisms occurring on or within rock substrata are variously known as 'lithobionts', 'lithobiontic' organisms, 'lithophytes' or 'lithophytic' organisms. Based on inhabiting location, they are classified in to various groups. Organisms growing attached to the external surfaces of rocks are termed 'epiliths 'or 'epilithobionts', those growing underside of rocks in contact with the soil are termed 'hypoliths', and those inside rocks are termed 'endoliths' or 'endolithobionts'. Further, the endoliths are called 'chasmoendoliths' if they inhabit fissures and cracks in rocks open to the rock surface, 'cryptoendoliths' if they dwell within structural cavities or natural pore spaces of rocks, and 'euendoliths' (true endoliths) if they actively penetrate in to the interior of rocks forming tunnels (Golubic *et al.*, 1981; Büdel, 1999). Euendoliths are often called rock-boring organisms. In their life cycle or at various stages of colonisation, lithobionts can be partially epilithic and endolithic or have epilithic and endolithic phases. Cyanobacteria can grow as epiliths on the stone surface or as endoliths in the pores, fissures, cracks and cavities of the stone (Crispim and Gaylarde, 2005; Gaylarde *et al.*, 2012). Epilithic cyanobacteria comprise majority of the rock-dwelling cyanobacteria.

Occurrence and diversity of lithophytic cyanobacteria on Indian temples and monuments

As lithophytes, cyanobacteria successfully colonize and inhabit various lithic habitats, such as natural rocks/stones as well as temples, monuments, heritage structures and buildings (Büdel, 1999; Crispim *et al.*, 2006; Pandey, 2013). Since cyanobacteria are resistant to desiccation and high solar radiations, their growth on stone surfaces is favoured in tropical countries (Gaylarde and Gaylarde, 2005; Gaylarde *et al.*, 2012). Both coccoid (unicellular and colonial) and filamentous forms colonize and grow on stone monuments and buildings. The most widespread and commonly reported genera on the Indian stone temples and monuments include *Scytonema, Lyngbya, Gloeocapsa, Chroococcus, Nostoc, Synechococcus, Anabaena, Phormidium, Plectonema, Leptolyngbya, Gloeothece, Aphanothece, Cyanothece, Calothrix, Tolypothrix, Stigonema* etc.

The occurrence and diversity of lithophytic cyanobacteria on temples and monuments located in different parts/states of India have been reported by various researchers as summarized in Table 1.

Effects of lithophytic cyanobacteria on temples and monuments

Various studies from different parts of the world indicates that the colonization, growth and activities of lithophytic cyanobacteria and other microorganisms on monuments and historic buildings cause their biodeterioration that is manifested as both aesthetic and structural damage (Crispim *et al.*, 2003; Crispim *et al.*, 2004; Crispim *et al.*, 2006; Crispim and Gaylarde, 2005; Gaylarde *et al.*, 2012; Gaylarde, 2020; Ortega-Morales *et al.*, 2000; Macedo *et al.*, 2009; Scheerer *et al.*, 2009; Lamenti *et al.*, 2000; Adhikary and Kovacik, 2010; Ortega-Calvo *et al.*,1993; Warscheid and Braams, 2000; Zurita *et al.*, 2005). Because of their peculiar features, cyanobacteria are usually primary colonizers of nutrient-poor, water-limited and light-exposed lithic substrata (Budel, 1999). Photosynthetic CO_2 fixation and, additionally in some species N_2 fixation, enable them to readily colonize and develop on lithic substratadevoid of any organic matter. As photoautotrophs and primary colonizers of lithic habitats, they promote the growth of heterotrophic microbes like bacteria and fungi, resulting in the formation of laminated phototrophic biofilms, also called subaerial biofilms (SAB), on light-exposed surfaces of monuments, buildings or bare rocks held together and adhered to underlying surfaces by extracellular polymeric substances (EPS) (Gorbushina, 2007; Gaylarde and Morton, 1999; Crispim and Gaylarde, 2005; Tomaselli *et al.*, 2000). Cyanobacterial EPS, which are variously called slimes, sheath and capsule, play crucial roles in adhesion, surface colonization, cell aggregation, and biofilms formation on lithic surfaces. In contrast to fungi and bacteria, cyanobacterial colonization and growth on lithic substrata is visually recognizable as patina or crust formation of distinct colour. Biodeterioration is generally caused by the interaction of co-existing populations of microbes (bacteria, cyanobacteria, green algae, fungi) on stone surfaces where they can act synergistically.

The colonization and growth of lithophytic cyanobacteria can affect stone-built temples, monuments and buildings directly or indirectly in various ways, ultimately resulting in their aesthetic and structural damage (Dakal and Cameotra, 2012; Macedo *et al.,* 2009; Crispim and Gaylarde 2005; Gaylarde and Morton, 1999). Their growth and activities modify the physical and chemical properties of stone temples and monuments. The potential effects of lithophytic cyanobacteria on stone temples and monuments are summarized in Fig. 1. Aesthetic damage occurs due to the unpleasant discoloration or disfigurement of wall surfaces of temples and monuments by cyanobacterial pigments, such as chlorophyll *a*, carotenoids, phycobilins and scytonemin, and by the formation of coloured crusts or patina. The structural or mechanical damage includes various known structural deformities, such as cracking, exfoliation, biopitting, textural changes, crumbling and fissure formation.

The pressure exerted by the growth of cyanobacterial cells, filaments or biofilms inside the pores and fissures of building stones can cause mechanical damage. Cyanobacterial EPS are implicated in weathering due to chelating and solubilising effects on rock/stone minerals, resulting in the weakening of the mineral lattice (Gaylarde and Gaylarde, 1999; Ortega-Morales *et al.,* 2000; Wessels and Büdel, 1995). The growth of cyanobacteria or development of cyanobacteria-dominated biofilms or crusts on the surface of stone temples and monuments can cause changes in thermal properties of stone as discoloured surface absorbs more heat leading to increase in surface temperature which induces physical stress by expansion and contraction (Warscheid, 2000). Prolonged retention of water in cyanobacterial EPS or biofilms promotes water-mediated reactions e.g., hydrolysis of silicate minerals, dissolution of carbonates and formation of gypsum crust.

The metabolic products or organic matter produced by lithophytic cyanobacteria promote the growth of heterotrophic microbes, such as bacteria and fungi on temples and monuments which have stronger deteriorating activity (Tiano, 1993; Tomaselli *et al.,* 2000; Crispim *et al.,* 2003; Zurita *et al.,* 2005). Bacteria and fungi produce and release various inorganic acids and organic acids having corrosive effects which can solubilize the minerals of lithic substrata, leading to the weakening of the mineral matrix (Warscheid and Braams, 2000; Gaylarde *et al.,* 2003; Dakal and Cameotra, 2012; Wakefield and Jones, 1998). Fungal growth discolours temples and monuments due to production of pigment, melanin.

The mechanical action of fungi occurs due to the physical penetration of fungal hyphae in to the stone. The chemical actions are caused by the organic acids secreted by the fungi (Sterflinger and Krumbein, 1997; Warscheid and Braams, 2000; Burford *et al.,* 2003).

Lithophytic cyanobacteria are important and fast colonizers of stone temples and monuments. Deterioration of stone monuments and buildings is a complex process occurring as a result synergistic action of abiotic (physical and chemical) and biotic factors over time. Biodeterioration caused by various microorganisms is gaining attention as much as that caused by physical and chemical agents.

The climate of India, mostly being the tropical and sub-tropical, supports the rich diversity of lithophytic cyanobacteria. Many stone-built Indian temples, monuments and heritage buildings show low to high levels of bio-colonization and biodeterioration caused by various organisms, including cyanobacteria.

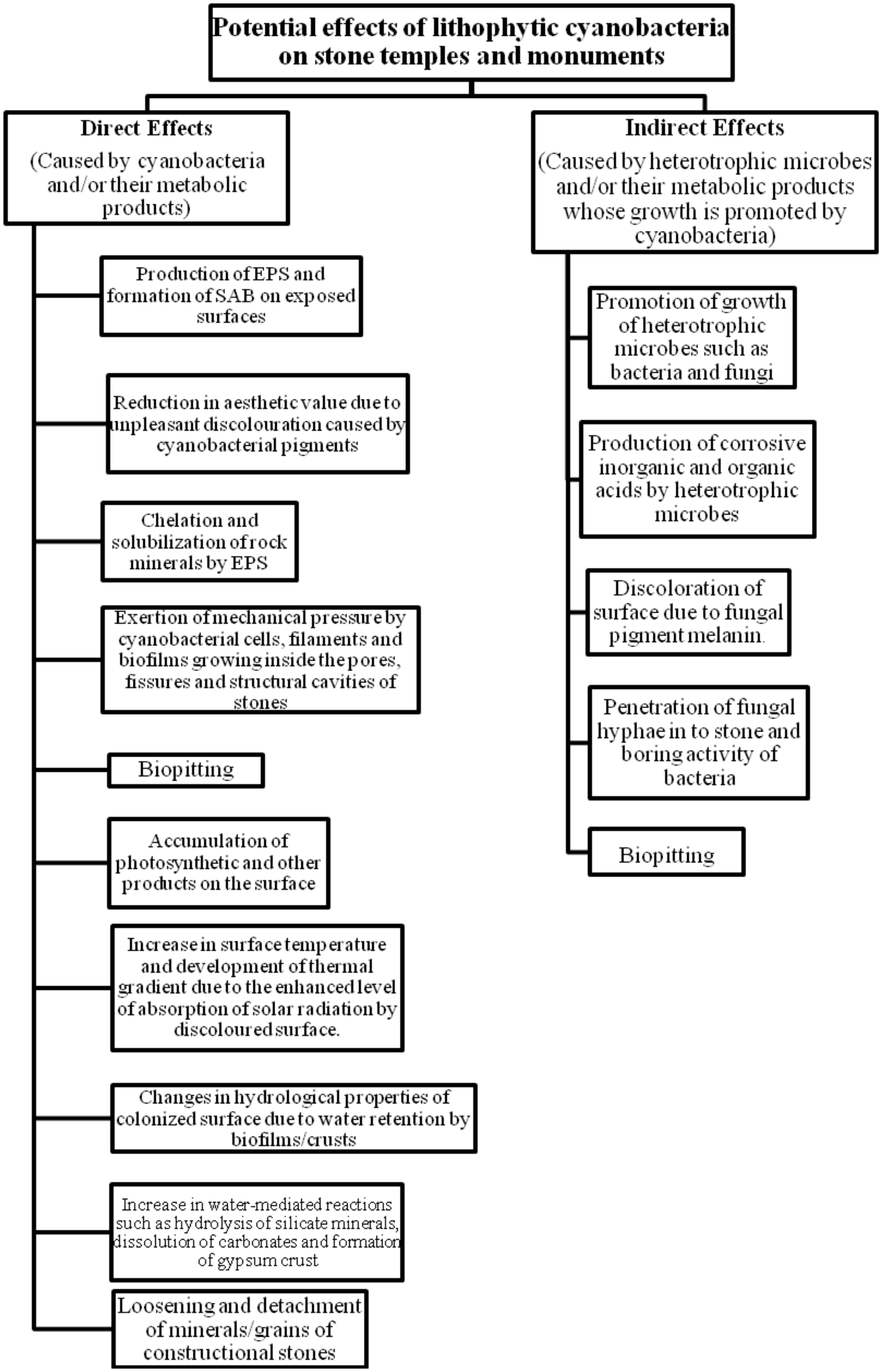
The lithophytic cyanobacteria are of scientific interest due to their enormous survival ability on exposed surfaces of lithic substrata and tolerance to various abiotic stresses. Epilithic cyanobacteria comprise a prominent component of biofilms that form on exposed surfaces of temples, monuments and buildings. Biodeterioration caused by cyanobacteria together with other microorganisms is a serious problem worldwide, offering a challenge to the conservation and restoration of lithic temples, monuments, heritage structures and buildings. Knowledge of the lithophytic cyanobacterial community of lithic temples, monuments and buildings is important for the study of the biodeterioration process as well as for the development of suitable control methods needed for the restorative conservation of temples, monuments and buildings.

Table.1 Lithophytic cyanobacteria reported on stone temples and monuments in India

Temples/Monuments	Cyanobacteria (Genus/Species)	References
Temples of Thanjavur district, Tamil Nadu	*Oscillatoria, Microcystis, Chroococcus, Gloeocapsa, Aphanocapsa, Synechococcus, Synechocystis, Myxosarcina, Spirulina, Phormidium, Lyngbya, Plectonema, Nostoc, Anabaena, Scytonema, Hapalosiphon*	Bhavani *et al.,* (2013)
Monuments and buildings of Odisha, Assam, Meghalaya, Rajasthan	*Chroococcus sp., Cyanosarcina spp., Asterocapsa divina, Gloeocapsopsis spp., Chroococcidiopsis spp., Gloeocapsa spp., Gloeothece sp., Aphanothece spp., Cyanothece, Phormidium spp., Pseudophormidium, Porphyrosiphon, Microcoleus, Leptolyngbya spp., Schizothrix spp., Nostoc, Plectonema, Scytonema, Tolypothrix, Calothrix, Stigonema, Westiellopsis*	Samad and Adhikary (2008)
Temples of western Odisha	*Aphanothece saxicola, Synechococcus elongatus, Cyanothece spp., Gloeothece rhodochlamys, Aphanocapsa spp., Asterocapsa spp., Chroococcus spp., Cyanosarcina spp., Gloeocapsopsis, Gloeocapsa kuetzingiana, Chroococcidiopsis, Hapalosiphon spp., Fischerella spp., Westiellopsis*	Pradhan *et al.,* (2018)
Monuments of Bhubaneswar, Odisha	*Chroococcus minor, C. lithophilus, C. pallidus, C. schizodermaticus, Asterocapsa divina, Gloeocapsa spp., Gloeocapsopsis spp., Gloeothece, Phormidium spp., Plectonema, Leptolyngbya, Nostoc, Scytonema, Hassallia, Tolypothrix, Calothrix, Stigonema, Westiellopsis*	Adhikary and Kovacik (2010)
Terracotta temples of Bishnupur, West Bengal	*Gloeocapsa, Aphanothece, Gloeothece, Cyanosarcina, Chroococcus, Lyngbya, Nostoc*	Mandal and Rath (2013)

Temples, monuments and sculptures of Uttar Pradesh, Odisha, West Bengal, Maharashtra, Karnataka, Tamil Nadu and Delhi	*Gloeothece, Myxosarcina spp., Nostoc spp., Calothrix, Tolypothrix spp., Fischerella, Westiellopsis, Stigonema*	Pattanaik and Adhikary (2002)
Temples of Thanjavur district, Tamil Nadu	*Oscillatoria sp., Lyngbya sp., Phormidium sp.*	Deepa *et al.*, (2011)
Temples of Uttarakhand, India	*Gloeocapsa sp., Gloeothece sp., Chlorogloeopsis sp., Calothrix sp., Plectonema sp., Nostoc commune, Fischerella sp., Tolypothrix tenuis*	Pandey (2011)
Temples and monuments of different regions of India	*Tolypothrix spp., Gloeocapsopsis spp., Lyngbya spp., Plectonema spp., Phormidium, Gloeothece, Myxosarcina, Chroococcidiopsis, Nostoc, Calothrix, Chlorogloeopsis, Fischerella, Hapalosiphon*	Tripathi *et al.*, (1999)
Monuments at Santiniketan, West Bengal	*Scytonema millei, Scytonema* sp., *Tolypothrix campylonemoides*	Keshari and Adhikary (2013)
Temples, monuments and cavesof Odisha, Tamil Nadu, West Bengal, Maharashtra, Chhattisgarh	*Hassallia, Tolypothrix, Scytonema, Lyngbya, Nostoc, Calothrix*	Keshari and Adhikary (2014)
Monuments at Santiniketan, West Bengal	*Hassallia lithophila*	Keshari *et al.*, (2019)
Temples and rock-cut caves of Bhubaneswar, Odisha	*Gloeocapsa, Gloeocapsopsis, Porphyrosiphon, Leptolyngbya, Lyngbya, Phormidium, Nostoc, Scytonema, Tolypothrix, Hassallia and Stigonema, Cyanosarcina, Pseudophormidium, Schizothrix, Plectonema, Dichothrix* and *Calothrix*	Adhikary *et al.*, (2015)
Temples and monuments of Thanjavur and Thiruvarur district, Tamil Nadu	*Gloeocapsopsis, Lyngbya, Phormidium, Chroococcus, Nostoc, Tolypothrix*	Madhavan *et al.*, (2008)

Fig.1 Potential effects of lithophytic cyanobacteria on stone temples and monuments



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