The distribution and ecological factors of aerial algae inhabiting stoneworks in Korea

Mi-Ae Song¹, Ok-Jin Kim¹ and Ok-Min Lee^{1,*}

¹Department of Life Science, College of Natural Science, Kyonggi University, Suwon 443-760, Korea

The physico-chemical and environmental factors of stoneworks were examined from March 2009 to October 2010, and aerial algae living on 24 stoneworks in Korea were identified. Fifty aerial algae were found in 24 stoneworks. Of the 50 taxa, 30 taxa were cyanophytes, 16 taxa were bacillariophytes, 3 taxa were chlorophytes, and 1 taxon was a xanthophyte. Nine species, including *Aphanocapsa rivularis*, which is known to only live in aquatic conditions, inhabited both aquatic and aerial environments. *Synechococcus aeruginosus*, *Scytonema coactile* var. *thermalis*, *S. coactile* var. *minor*, *Stigonema ocellatum* f. *ocellatum*, and *Oscillatoria boryana* were newly recorded in Korea. As a result of a correlation analysis between algae and the physico-chemical and ecological environmental factors, the taxa were divided into the bryophyte group, the humidity group, and the dry group. Although the bryophyte group was included within the humidity group, it was separated from the dry group. Taxa in the bryophyte group including *Nostoc commune* which was distributed in more humid areas than those in the humidity group. However, dry group taxa including *Chroococcus pallidus* were distributed in lower humidity than that of the two other groups. Correlations among other environmental factors were tested to identify other factors that could substitute for humidity and light intensity. As a result, tree distance, water distance, and plant coverage were replaceable environmental factors.

Key Words: aerial algae; bacillariophytes; chlorophytes; cyanophytes; stoneworks; xanthophytes

INTRODUCTION

Aerial algae are algae that live in rock faces, earthen rocks, stone walls, and plants but not in water. Edaphophytes can also be included as aerial algae (Chung 1993). Studies on algae have mostly concentrated on aquatic algae, and studies conducted on aerial algae have mostly focused on biological pollution and preventive stone cultural heritage research (National Research Institute of Cultural Heritage 2008). Some taxa in *Protococcus*, *Trentepohlia*, *Cephaleuros*, *Scytonema*, *Nostoc*, *Schizothrix*, *Stigonema*, *Chlorococcum*, and *Trentepohlia* are known as aerial algae. According to Chung (1979), 90 taxa are listed as aerial algae, and 45 taxa were identified

in Korea in Chung (1993). Additionally, 41 aerial algae taxa have been identified in Korea in studies by Chang et al. (1998), but only a few studies have been conducted on aerial algae.

In research on aerial algae habitat distribution, it was determined that cyanophytes, such as *Gloeocapsa* sp. and *Lyngbya* sp., inhabit the Muryong Royal Tomb in Gongju (Kim et al. 2001). Additionally, studies on *Chlorella* attached to a stone Buddha (Klochova and Kim 2005), and aerial algae distributed on five (Lim and Lee 2008a) and eight (Kim et al. 2010) stone cultural properties have been conducted in Korea.

© This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Received January 25, 2012, Accepted September 24, 2012

*Corresponding Author

E-mail: omlee@kyonggi.ac.kr

Tel: +82-31-249-9643, Fax: +82-31-241-0860

Fig. 1. Photographs the algae habitats sampled in Korea at the 24 stoneworks sites from 2009 to 2010. (A & B) Unjusa temple (lichen and aerial algae). (C & D) Jucksung-myeon stone wall (bryophyte). (E & F) Yeondae small temple (lichen and aerial algae).

According to Hyvert (1972), 39 aerial algae species have been identified, and studies on the genus *Synechococcus* have reported that it lives endolithically with lichen in the church of Minas Gerais, Brazil (Allsopp et al. 2004). Five taxa including *Coccomyxa* are green algae that live on marble (Lamenti et al. 2000), and *Chlorella* has been discovered in the Maya ruins of Mexico (Videla et al. 2000). Research about microalgae in stoneworks located in Spain (Sarró et al. 2006) and a study of cyanophytes that inhabit a church wall located in Porto Alegre, Brazil (Crispim et al. 2004) has also been performed. The main objectives of this study were to identify aerial algae living in stoneworks and to record new species in Korea. In addition, ecological characteristics of the identified algae

were investigated by analyzing the ecological factors related to their distribution.

MATERIALS AND METHODS

Collections of aerial algae were sampled at Gyeonggi-do, Jeolla-do, Gyeongsang-do, and Chungcheong-do on 24 stoneworks from March 2009 to October 2010 (Table 1, Fig. 1). The aerial algae samples were collected from more than one part and in every aspect of the stoneworks using a soft brush and sterilized depressor. A 5 × 5 cm² quadrat was used for quantitative analysis. Each sample was sealed and refrigerated in a light-tight container with

sterilized distilled water and transferred to the laboratory (Crispim et al. 2004). Some of the samples were stored fixed in 1% formalin. Among them, the unrecorded Korean species were cultured indoors, and maintained in the algal culture collection of Kyonggi University (ACKU).

An analysis of physico-chemical environmental factors such as surface temperature of the stonework, light intensity, and humidity were conducted for all sampling dates. Temperature was measured with a stem thermometer, and surface temperature was measured with a Testo 830-T1 (Testo, Lenzkirch, Germany), humidity was measured with a Testo 625 (Testo), and light intensity was assessed with a LX-1108 instrument (Lutron, Taipei, Taiwan). Temperature, humidity, and light intensity have tremendous effects on algae distribution; however, these variables largely depend on the season and time of collection. Therefore, we measured plant coverage, canopy, distance to trees, and distance to water to identify relatively stable environmental factors that could replace temperature, humidity, and light intensity (Fig. 2).

Fig. 2. Diagram of the method for measuring the environmental factors.

Table 1. Information on the 24 stoneworks from which algae were collected from March 2009 to October 2010

Code	Stonework	Status	Date	Location
a	Gwang-gyo Mountain 1-1	Na	Mar 2009	Gwang-gyo Mountain, Gyeonggi-do
b	Gwang-gyo Mountain 1-2	Na		Gwang-gyo Mountain, Gyeonggi-do
c	Gwang-gyo Mountain 1-3	Na		Gwang-gyo Mountain, Gyeonggi-do
d	Gwang-gyo Mountain 2-1	Na		Gwang-gyo Mountain, Gyeonggi-do
e	Gwang-gyo Mountain 2-3	Na		Gwang-gyo Mountain, Gyeonggi-do
f	Gwang-gyo Mountain 3-1	Na		Gwang-gyo Mountain, Gyeonggi-do
g	Gwang-gyo Mountain 3-2	Na		Gwang-gyo Mountain, Gyeonggi-do
h	Gwang-gyo Mountain 3-3	Na		Gwang-gyo Mountain, Gyeonggi-do
i	Unjusa Temple A1	MH	Apr 2009	Unjusa Temple, Jeollanam-do
j	Unjusa Temple A4	MH		Unjusa Temple, Jeollanam-do
k	Unjusa Temple A5	MH		Unjusa Temple, Jeollanam-do
l	Unjusa Temple A6	MH		Unjusa Temple, Jeollanam-do
m	Unjusa Temple A10	MH		Unjusa Temple, Jeollanam-do
n	Unjusa Temple stone wall 1	MH	Jul 2009	Unjusa Temple, Jeollanam-do
o	Unjusa Temple stone wall 2	MH		Unjusa Temple, Jeollanam-do
p	Yeondae small temple A-1	MH	Aug 2009	Yeongyang-gun, Gyeongsangbuk-do
q	Yeondae small temple A-2	MH		Yeongyang-gun, Gyeongsangbuk-do
r	Yeondae small temple A-3	MH		Yeongyang-gun, Gyeongsangbuk-do
s	Yeondae small temple B-1	MH		Yeongyang-gun, Gyeongsangbuk-do
t	Yeondae small temple B-2	MH		Yeongyang-gun, Gyeongsangbuk-do
u	Yeondae small temple B-3	MH		Yeongyang-gun, Gyeongsangbuk-do
v	Stone wall 1 of Jucksung-myeon, Danyang-gun	MH	Jul 2010	Danyang-gun, Chungcheongbuk-do
w	Stone wall 2 of Jucksung-myeon, Danyang-gun	MH		Danyang-gun, Chungcheongbuk-do
x	Stone wall in Pyeongchang-gun	MH	Oct 2010	Pyeongchang-gun, Gangwon-do

Na, natural stone; MH, modified for human use.

Plant coverage was considered the distribution of woods within a 10 m radius of the stoneworks as a percentage. The number of trees screening light was measured within a 1 m radius of the stoneworks as a percentage to assess the canopy. Tree distance was considered the closest distance to a tree within a 5 m radius. The water distance was the closest distance to a river or lake within a 1,000 m radius. Biological pollution coverage was calculated by measuring the bryophyte area using AutoCAD 2008 (Autodesk Inc., San Rafael, CA, USA). The taxonomic classification system was based on Hirose et al. (1977), and aerial algae were identified referring to Prescott (1973), Prescott et al. (1972, 1977, 1981, 1982), Chung (1993), John et al. (2002), and Wehr and Sheath (2003). Dominant species were analyzed by relative abundance. The collected samples were examined under

a light microscope (400-1,000×) to determine the total number and the dominant species. Light microscopy was carried out using an Olympus BX41 microscope (Olympus, Tokyo, Japan) equipped with Nomarski differential interference optics. Species newly recorded in Korea were illustrated using a drawing attachment together with light microscope photographs. SPSS version 12.0 (SPSS Inc., Chicago, IL, USA) was used to analyze the relationships between aerial algae and the environmental factors.

RESULTS

Table 2 shows the results of the physico-chemical, and ecological environmental factors of the stoneworks where the aerial algae was found. The air temperature

Table 2. The physico-chemical and ecological environmental factors at 24 stoneworks from March 2009 to October 2010

Site	Cov (%)	Can (%)	TD (m)	WD (m)	T (°C)	ST (°C)	Hu (%)	L (lux)	BPC (%)	
									Br	Li & Al
a	20	70	5	6	18.2	17.5	41.4	3,915	0	9.9
b	20	70	5	6	18.2	17.5	41.4	3,922	0	69.3
c	20	70	5	6	18.2	17.5	41.4	3,950	0	72.8
d	60	30	0.6	30	12.2	7.5	58.7	162	1.2	29.3
e	60	30	0.5	25	12.2	8.5	58.7	202	7.0	43.6
f	30	60	0.3	50	17.5	15.0	70.7	1,387	0	9.7
g	80	50	0	70	21.2	15.0	59.3	3,071	0	52.1
h	10	80	2	50	20.1	15.5	65.7	2,617	0	86.1
i	30	2	5	1,000	10.2	7.5	-	-	0	100
j	10	0	5	1,000	11.1	7.5	-	-	0	100
k	0	0	5	1,000	10.2	7.5	-	-	0	97.5
l	10	0	3	1,000	10.2	7.5	-	-	0	96.3
m	30	0	3	1,000	10.4	7.5	-	-	0	99.0
n	80	95	0.1	0.1	27.2	23.5	85	2,500	16.2	36.3
o	80	0	0.1	0.1	28.9	27.5	84.2	7,880	1.8	55.7
p	50	60	0	1,000	26.7	28	80.4	18,500	1.3	95.5
q	50	80	0	1,000	26.7	30	80.4	18,500	0	94.2
r	50	80	0	1,000	26.7	29	70.2	39,000	40.6	39.0
s	50	80	0	1,000	25	23	73	1,957	42.7	51.9
t	50	80	0	1,000	25	23.5	80	3,950	0	96.4
u	50	80	0	1,000	25	22.5	90	2,100	70.5	23.8
v	70	100	0	50	-	21.5	-	-	99.0	1.0
w	70	60	0	50	-	-	-	-	62.0	38.0
x	40	0	0.1	0.3	14.6	13.0	-	-	0	59.6

Cov, plant coverage (%); Can, canopy (%); TD, tree distance (m); WD, water distance (m); T, temperature (°C); ST, surface temperature (°C); Hu, humidity (%); L, light intensity (lux); BPC, biological pollution coverage (%); BR, bryophytes; Li, lichens; Al, aerial algae.

was 10.2-29.9°C and surface temperature was 7.5-30.0°C. Humidity was 41.4-90.0%. The light intensity values were the highest at the Yeondae small temple A-3 (39,000 lux), and the lowest were recorded at Gwang-gyo mountain 2-1 (162 lux). Due to strong wind, measuring the humidity, and light intensity at the Unjusa Temple, the stone wall at Jucksung-myeon, Danyang-gun, and the stone wall at Pyeongchang-gun was difficult. Plant coverage at the three sites including Gwang-gyo Mountain 3-2 had the highest value at 80%, whereas the Unjusa Temple A5 was not affected by plant coverage with a value of 0%. Stone wall 1 at Jucksung-myeon, Danyang-gun, which was a site where light was screened by trees, had a canopy value of 100%. Five sites, including Unjusa Temple A4, had a 0% canopy value. Tree distance ranged from 0 to 5 m, indicating that most sites were affected by trees. Water distance values were 0.1-1,000 m.

Four phyla, 4 classes, 8 orders, 4 suborders, 13 families, 23 genera, 46 species, 3 varieties, and 1 forma were collected and identified as aerial algae (Table 3). Cyanophytes were the most dominant taxa, with 3 orders, 2 suborders, 5 families, 10 genera, 26 species, 3 varieties, and 1 forma. Only one species, *Botryococcus braunii*, was considered a xanthophyte, and bacillariophytes had 2 orders, 2 suborders, 5 families, 9 genera, and 16 species. Chlorophytes had 2 orders, 2 families, 2 genera, and 3 species.

Stone wall 1 at Jucksung-myeon and Danyang-gun had the most taxa among the stoneworks with 21 taxa including *Aphanocapsa elachista*. Gwang-gyo Mountain 3-1 had only one taxon, *Chroococcus varius* (CHVA). *C. varius* had the most varied growth range, appearing in 21 different stoneworks including Gwang-gyo Mountain 1-2. *Proto-coccus viridis*, which appeared most frequently in Lim and Lee (2008b), was found at five sites including Gwang-gyo Mountain 1-1.

The habitats of all taxa were evaluated after reviewing other studies (Table 3). Five taxa, including *Synechococcus aeruginosus*, were newly recorded in Korea. Among the 50 taxa, 37 taxa including *Aphanocapsa elachista* are known to inhabit aerial and aquatic environments. Additionally, 3 taxa, including *Chroococcus bituminosus*, were distributed only in aerial environments.

Phylum Cyanophyta

Class Cyanophyceae

Order Chroococcales

Family Chroococcaceae

Synechococcus aeruginosus Nageli

Cell long and cylindrically shaped, with a width of 6-16 µm and length of 13-30 µm. Light blue-green color, with many granules; lives in freshwater and hot springs (Hirose et al. 1977).

Synechococcus aeruginosus (SYAE) lives in Sola lake in Taba Egypt (Badawy et al. 1999). In Korea, one species, *Synechococcus lividus*, was identified under the genus *Synechococcus* (Chung 1993). That study revealed that *S. lividus* lives on the surfaces of stone walls inhabited by bryophytes. The tree distance from the stoneworks was 0 m, with 50-70% plant coverage, which was probably due to its relatively high water composition.

Sites of collection. t, u, v (Figs 3E & 4A).

Order Nostocales

Suborder Nostochineae

Family Scytonemataceae

Scytonema coactile Montagne var. *thermalis*

Geitler

Cell olive or purple-green in color. Main axis pseudo-branched and filamentous. Sheaths have no layered structure or color. Cell is (11)-15-18 µm in diameter and becomes narrower at the tip. Trichome is cylindrical with width of 9-11 µm and length of 7-20 µm. Heterocysts are cylindrical, and it inhabits hot springs (Hirose et al. 1977).

Scytonema coactile var. *thermalis* (SCTH) has been found in Japan (Hirose et al. 1977), and we found that it lives on stone. Water distance was >1,000 m, and tree distance was 0-5 m.

Sites of collection. k, p, r, s, u (Figs 3A & 4C).

Order Nostocales

Suborder Nostochineae

Family Scytonemataceae

Scytonema coactile Montagne var. *minor* Wille

Cell is thick and 1 mm in width. Pseudo-branching mostly originates from main axis. It has a yellow-brown colored sheath without a layered structure, and a diameter of 14-16 µm. Trichomes are cylindrical with no joints; width is 8-10 µm. Heterocysts are cylindrical or square shaped, and it inhabits hot springs (Hirose et al. 1977).

Scytonema coactile var. *minor* (SCMI) is known to inhabit Japan and China; however, only *S. crispum* and *S. myochorus* has been identified locally (Chung 1993). In this study, *S. coactile* var. *minor* appeared at 10 sites including Gwang-gyo Mountain 1-1 and seemed to be affected by trees.

Table 3. A list of aerial algae and their habitats collected at 24 stoneworks from March 2009 to October 2010

Species		a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	Habitats
Phylum	Cyanophyta																									
Class	Cyanophyceae																									
Order	Chroococcales																									
Family	Chroococcaceae																									
	<i>Aphanocapsa elachista</i>																						+			W (Chung 1993, John et al. 2002), R (Lim and Lee 2008a)
	<i>A. grevillei</i>																						+	+		W, R, S (John et al. 2002)
	<i>A. pulchra</i>																					+	+	+		W (Chung 1993), S (Tiwari 1972)
	<i>A. rivularis</i>																					+	+			W (Chung 1993)
	<i>Aphanothece naegelii</i>																					+	+			W, R, M (Chung 1993), S (Tiwari 1972)
	<i>Chroococcus bituminosus</i>																						+			R (Lim and Lee 2008a)
	<i>C. minutus</i>		+								+	+	+			+							+			W (John et al. 2002), R (Lim and Lee 2008a)
	<i>C. pallidus</i>										+					+										W (Chung 1993), R (Gomez et al. 2003)
	<i>C. varius</i>		+		+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	W (Naz et al. 2004b), R (Lim and Lee 2008a, 2008b, Uher 2008)
	<i>Synechococcus aeruginosus</i> ^a																						+	+	+	W, M (John et al. 2002), R (Bellinzoni et al. 2003)
	<i>Synechocystis aquatilis</i>								+			+			+	+							+			W (Chung 1993), R (Lim and Lee 2008a, 2008b), S (Naz et al. 2004b)
Order	Nostocales																									
Suborder	Nostochineae																									
Family	Nostocaceae																									
	<i>Anabaena circinalis</i>																							+		W (John et al. 2002), S (Ghadai et al. 2010)
	<i>Nostoc commune</i>																							+		W, S, M (John et al. 2002), R (Gomez et al. 2003)
	<i>N. microscopium</i>																							+	+	W (John et al. 2002), R (Gomez et al. 2003, Uher 2008), M (West and Fritsch 1972)
Family	Scytonemataceae																									
	<i>Scytonema coactile</i> var. <i>minor</i> ^a		+	+		+				+	+		+	+		+								+	+	W (Hirose et al. 1977)
	<i>S. coactile</i> var. <i>thermalis</i> ^a											+				+			+	+			+			W (Hirose et al. 1977)
	<i>S. crispum</i>																							+		W (John et al. 2002), R (Lim and Lee 2008a)
Suborder	Oscillatorineae																									
Family	Oscillatoriaceae																									
	<i>Lyngbya aerugineo-coerulea</i>		+																							W, S (Chung 1993)
	<i>L. birgei</i>																							+		W, S (Chung 1993)
	<i>Oscillatoria boryana</i> ^a																							+		W (Naz et al. 2004a)
	<i>O. chlorina</i>					+																		+	+	W, S (Chung 1993)
	<i>O. geminata</i> var. <i>subphurea</i>																							+		W (Chung 1993)
	<i>O. iwanoffiana</i>																							+		W (Chung 1993, Hirose et al. 1977)
	<i>O. limosa</i>								+																	W (Chung 1993), S (John et al. 2002)
	<i>O. okeni</i>						+																			W (Chung 1993, Naz et al. 2004a), S (Tiwari 1972)
	<i>O. sancta</i>																							+		W (Chung 1993, Naz et al. 2004a), S (John et al. 2002)

Table 3. Continued

Species	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	Habitats
	<i>O. terebriformis</i>																				+				W (Chung 1993, John et al. 2002, Naz et al. 2004a), S (Naz et al. 2004a)
	<i>O. uncinata</i>																						+		W (Chung 1993), S (Cavacini 2001)
Order	Stigonematales																								
Family	Stigonemaceae																								
	<i>Stigonema mamillosum</i>																						+		W (Chung 1993), R (Chung 1993, John et al. 2002)
	<i>S. ocellatum</i> f. <i>ocellatum</i> ^a	+		+			+	+	+	+	+	+	+	+	+			+	+	+	+	+			W, R, S, M (John et al. 2002)
Phylum	Chrysophyta																								
Class	Bacillariophyceae																								
Order	Pennales																								
Suborder	Raphidineae																								
Family	Naviculaceae																								
	<i>Cymbella delicatula</i>																						+		W (Chung 1993)
	<i>C. sillesiaca</i>											+						+		+					W (Chung 1993), R (Poulíčková and Hašler 2007)
	<i>Gomphonema acuminatum</i>																						+		W (Chung 1993)
	<i>G. parvulum</i>																						+		W (Chung 1993), R (Poulíčková and Hašler 2007)
	<i>Navicula contenta</i>						+											+					+	+	W (Chung 1993), R (Poulíčková and Hašler 2007)
	<i>N. cryptocephala</i>																						+		W (Chung 1993), R (Lim and Lee 2008a)
	<i>N. goeppertiana</i>	+			+		+	+	+	+	+	+	+	+	+	+		+				+	+	+	W (Chung 1993), R (Poulíčková and Hašler 2007)
	<i>N. subminuscula</i>							+					+												W (Chung 1993)
Family	Diatomaceae																								
	<i>Pinnularia borealis</i>					+				+	+	+	+	+	+	+		+				+	+	+	W (Chung 1993), R (Poulíčková and Hašler 2007, Uher 2008), S (Cavacini 2001)
Family	Achnanthaceae																								
	<i>Achnanthes convergens</i>																						+		W (Chung 1993)
	<i>A. inflata</i>																							+	W (Chung 1993), R (Lowe et al. 2009)
	<i>A. minutissima</i>																						+		W (Chung 1993), R (Poulíčková and Hašler 2007)
Family	Nitzschiaceae																								
	<i>Nitzschia frustulum</i>																						+		W (Chung 1993), R (Hyvert 1972)
	<i>Hantzschia amphioxys</i>					+					+	+			+	+							+	+	W (Chung 1993), R (Poulíčková and Hašler 2007)
Order	Centrales																								
Suborder	Coscinodiscineae																								
Family	Melosiraceae																								
	<i>Melosira varians</i>																					+	+		W (Chung 1993), R (Poulíčková and Hašler 2007)
	<i>Orthoseira roeseana</i>																						+		W (Chung 1993), R (Chung 1993, Poulíčková and Hašler 2007)
Phylum	Chlorophyta																								
Class	Chlorophyceae																								
Order	Ulotrichales																								
Family	Ulotrichaceae																								

Table 3. Continued

Species		a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	Habitats
Order Family	<i>Klebsormidium crenulatum</i>			+								+				+							+	+		W, S (John et al. 2002), R (Lim and Lee 2008 <i>b</i> , Uher 2008)
	<i>K. dissectum</i>																						+	+		R (Lim and Lee 2008 <i>b</i>), S (John et al. 2002)
	Chaetophorales																									
	Protococcaceae																									
	<i>Protococcus viridis</i>			+									+				+		+					+		R (Lim and Lee 2008 <i>a</i> , 2008 <i>b</i>), S (Chung 1993)
Phylum	Xanthophyta																									
Class	Xanthophyceae																									
Order	Mischococcales																									
Family	Chlorobotrydaceae																									
	<i>Botryococcus braunii</i>																							+		W (Chung 1993), R (Lim and Lee 2008 <i>a</i>)
	Total taxa	2	5	2	2	7	1	6	3	6	7	10	5	5	6	13	5	8	4	9	6	14	20	16	2	

W, water; R, rock; S, soil; M, moss.

^aNewly recorded species.**Sites of collection.** a, b, e, i, k, l, m, o, v, w (Figs 3C & 4D).

Order Stigonematales

Family Stigonemataceae

Stigonema ocellatum (Dillwyne) Thuret f.
ocellatum

Cell shaped like grass or a thread; 25-50 µm wide with irregular branching. Usually exists as a single filament, but occasionally can be found as double filaments. Branches are slightly slimmer than the main axis. Sheath is relatively thick, and may have yellow, yellow-brown, or no color. Trichomes are elliptical or square-shaped, and it inhabits humid dirt, rocks, and grass (Hirose et al. 1977).

Stigonema ocellatum f. *ocellatum* has been studied on rocks exposed to natural light in Venezuela (Lakatos et al. 2001). In particular, it was found in places far away from water in the Australian study; however, we found it on stoneworks exposed to aerial algae without any relationship to water distance.

Sites of collection. c, e, g, h, l, j, l, m, r, s, t, u, v, w (Figs 3B & 4E).

Order Nostocales

Suborder Oscillatorineae

Family Oscillatoriaceae

Oscillatoria boryana Kützing

Cell dark colored; trichomes are flexible in the shape of a wave. The cell continuously folds, and length is less than or equal to half the width. Width of the cell is 6-8 µm,

and length is 4-6 µm. The apical cell is circular or a sharp circular cone, and has no calyptra (Hirose et al. 1977).

Oscillatoria boryana has been found in India (Kalavathi et al. 2001), and some studies have reported it in Japan, China, and North America (Hirose et al. 1977). We found it at one site, the Yeondae small temple A-3, with a tree distance of 0 m, and a water distance of >1,000 m. These results indicates that it maintains humidity using trees.

Site of collection. r (Figs 3D & 4B).

Cyanophytes were dominant at 22 sites among the aerial algae (Table 4). In particular, cyanophytes dominated by >50% at 15 sites, including Gwang-gyo mountain 1-1 (Kim et al. 2010). *Hantzschia amphioxys* (HAAM) and *Cymbella delicatula*, which are bacillariophytes were dominant at the Yeondae small temples A-1 and A-2. HAAM is known to be found at high humidity sites with bryophytes (Lim and Lee 2008a, Kim et al. 2010). Filamentous cyanophytes of *Scytonema*, *Stigonema*, *Oscillatoria*, and *Nostoc* were dominant at 15 sites including Gwang-gyo Mountain 1-1. Coccoid-shaped cyanophytes such as *Chroococcus* and *Aphanocapsa* were dominant at seven sites including Gwang-gyo Mountain 1-2.

A principal component analysis was conducted to identify the relationships between the aerial algae and ecological factors. The varimax method (Kim et al. 2007) was used to obtain the results (Fig. 5).

All species were divided into ecological groups according to the correlation coefficients. The identified species were divided into biological pollution coverage of bryophyte (Br), high humidity (Hu), and dry (Dry) groups with

Fig. 3. Microscopic photographs of newly recorded species in Korea found at 24 stoneworks from 2009 to 2010. (A) *Scytonema coactile* var. *thermalis*. (B) *Stigonema ocellatum* f. *ocellatum*. (C) *Scytonema coactile* var. *minor*. (D) *Oscillatoria boryana*. (E) *Synechococcus aeruginosus*. Scale bar represents: A-E, 10 μ m.

Fig. 4. Illustrations of newly recorded species in Korea found at 24 stoneworks from 2009 to 2010. (A) *Synechococcus aeruginosus*. (B) *Oscillatoria boryana*. (C) *Scytonema coactile* var. *thermalis*. (D) *Scytonema coactile* var. *minor*. (E) *Stigonema ocellatum* f. *ocellatum*. Scale bars represents: A-E, 10 μ m.

Fig. 5. Principal component analysis plot of aerial algae from 24 stoneworks in Korea during 2009 to 2010. Br, bryophyte coverage; Hu, humidity; Dry, negative correlation between humidity and canopy. ACIN, *Achnanthes inflata*; APEA, *Aphanocapsa eachista*; ANCI, *Anabaena circinalis*; APRI, *Aphanocapsa rivularis*; APNA, *Aphanocapsa pulchra*; APPU, *Aphanocapsa pulchra*; CHBI, *Chroococcus bituminosus*; CHMI, *Chroococcus minutus*; CHPA, *Chroococcus pallidus*; CHVA, *Chroococcus varius*; CYDE, *Cymbella delicatula*; CYSI, *Cymbella sillesiaca*; GOAC, *Gomphonema acuminatum*; HAAM, *Hantzschia amphioxys*; KLDI, *Klebsormidium dissectum*; LYAE, *Lyngbya aerugineo-coerulea*; LYBI, *Lyngbya birgei*; NACO, *Navicula contenta*; NACR, *Navicula cryptocephala*; NAGO, *Navicula goeppertiana*; NASU, *Navicula subminuscula*; NOCO, *Nostoc commune*; NOMI, *Nostoc microscopium*; ORRO, *Orthocheira roeseana*; OSBO, *Oscillatoria boryana*; OSCH, *Oscillatoria chlorina*; OSGE, *Oscillatoria geminata* var. *subphurea*; OSOK, *Oscillatoria okeni*; OSTE, *Oscillatoria terebriformis*; OSUN, *Oscillatoria uncinata*; PIBO, *Pinnularia borealis*; PRVI, *Protococcus viridis*; SCCR, *Scytonema crispum*; SCMI, *Scytonema coactile* var. *minor*; SCTH, *Scytonema coactile* var. *thermalis*; STMA, *Stigonema mamillosum*; STOC, *Stigonema ocellatum*; SYAE, *Synechococcus aeruginosus*; SYAQ, *Synechocystis aquatilis*.

Table 4. Dominant species at 24 stoneworks in Korea during March 2009 to October 2010

Site	Dominant species	%
a	<i>Scytonema coactile</i> var. <i>minor</i>	89.6
b	<i>Chroococcus varius</i>	61.8
c	<i>Stigonema ocellatum</i> f. <i>ocellatum</i>	71.1
d	<i>Oscillatoria chlorina</i>	75.0
e	<i>Stigonema ocellatum</i> f. <i>ocellatum</i>	62.3
f	<i>Chroococcus varius</i>	98.0
g	<i>Oscillatoria limosa</i>	53.1
h	<i>Chroococcus varius</i>	47.2
i	<i>Scytonema coactile</i> var. <i>minor</i>	53.2
j	<i>Scytonema coactile</i> var. <i>minor</i>	81.1
k	<i>Chroococcus minutus</i>	42.3
l	<i>Stigonema ocellatum</i> f. <i>ocellatum</i>	77.6
m	<i>Scytonema coactile</i> var. <i>minor</i>	43.7
n	<i>Chroococcus varius</i>	57.6
o	<i>Scytonema coactile</i> var. <i>minor</i>	44.7
p	<i>Hantzschia amphioxys</i>	49.8
q	<i>Cymbella delicatula</i>	44.0
r	<i>Scytonema coactile</i> var. <i>thermalis</i>	65.4
s	<i>Stigonema mamillosum</i>	31.2
t	<i>Aphanocapsa pulchra</i>	72.4
u	<i>Nostoc commune</i>	96.0
v	<i>Oscillatoria chlorina</i>	38.0
w	<i>Oscillatoria chlorina</i>	22.1
x	<i>Aphanocapsa grevillei</i>	89.1

a negative correlation with humidity and canopy (Fig. 5). Species in the Br group were cyanophytes and bacillariophytes such as *Nostoc commune* (NOCO), *Oscillatoria geminata* var. *subphurea* (OSGE), *Orthocheira roeseana* (ORRO) and *Navicula cryptocephala* (NACR). These species showed high correlation coefficients with bryophyte biological pollution coverage ranging from 0.68 to 0.84. The Dry included *Chroococcus pallidus*, HAAM, SCMI among others. The Hu group included CHVA, SCTH, *Pinnularia borealis* (PIBO), *Navicula goeppertiana* (NAGO), and SYAE.

DISCUSSION

Physico-chemical environmental factors vary greatly due to seasonal differences and the weather conditions on the date of collection. This seems to affect changes in aerial algae groups inhabiting stoneworks (Lim and Lee 2008a). Korean aerial algae now include total 108 taxa by adding 5 taxa from the present study. We found the following ten species which are aquatic species found in aerial conditions: *Aphanocapsa rivularis*, SCMI, SCTH, *Oscillatoria boryana*, OSGE, *O. iwanoffiana*, *Gompho-*

Table 5. Analysis of the correlations between environmental factors in the 24 stoneworks in Korea collected during March 2009 to October 2010

	Cov	Can	TD	WD	Tp	STp	Hu	L
Cov	1.00	0.31	-0.79**	-0.30	0.60**	0.50*	0.55*	0.06
Can		1.00	-0.37	-0.18	0.71**	0.68**	0.09	0.17
TD			1.00	0.10	-0.62**	-0.55**	-0.84**	-0.22
WD				1.00	-0.01	0.06	0.57*	0.54*
Tp					1.00	0.97**	0.72**	0.50*
STp						1.00	0.60*	0.66**
Hu							1.00	0.21
Lux								1.00

The results of the correlation analysis between environmental factors showed that humidity had significant correlations with tree distance, water distance, and plant coverage with values of -0.84, 0.57 and 0.55, respectively. Moreover, light intensity and water distance were correlated (correlation coefficient = 0.54).

Cov, plant coverage; Can, canopy; TD, tree distance; WD, water distance; Tp, temperature; STp, surface temperature; Hu, humidity; L, light intensity. * $p < 0.05$, ** $p < 0.01$, $n = 24$.

nema acuminatum, *Navicula subminuscula*, *Achnanthes convergens*, and *Cymbella delicatula* (Table 3). Species in the Br group were cyanophytes and bacillariophytes such as NOCO, OSGE, ORRO, and NACR. Algae in the genus *Nostoc* live mainly in terrestrial habitats and appear to be attached to lichen, fungi, bryophytes, and vascular plants (Rai et al. 2002). The Br group plays an important role in habits of aerial algae by providing humid conditions. PIBO, NAGO, HAAM of the Dry and Hu groups were classified as aerial diatoms and are found under conditions with 80% humidity (Uher 2008), and also in conditions of 40% humidity and high light (Kim et al. 2011); therefore, it was thought that these aerial algae live in a wide range of conditions.

Correlations among other environmental factors were tested to identify other environmental factors that could substitute for humidity and light intensity (Table 5). As a result, tree distance, water distance, and plant coverage were replaceable environmental factors.

ACKNOWLEDGEMENTS

This research was supported by the foundation research project (2011-0005974) of National Research Foundation of Korea and National Research Institute of Cultural Heritage (NRICH-1107-B01F-1).

REFERENCES

- Allsopp, D., Seal, K. & Gaylard, C. 2004. *Introduction to bio-deterioration*. 2nd ed. Cambridge University Press, Cambridge, 237 pp.
- Badawy, M. I., Abou-Waly, H. F. & Ali, G. H. 1999. Excretion products of algae and their occurrence in Solar Lake. Taba, Egypt. *Int. J. Environ. Health Res.* 9:233-243.
- Bellinzoni, A. M., Caneva, G. & Ricci, S. 2003. Ecological trends in travertine colonisation by pioneer algae and plant communities. *Int. Biodeterior. Biodegrad.* 51:203-210.
- Cavacini, P. 2001. Soil algae from northern Victoria Land (Antarctica). *Polar Biosci.* 14:45-60.
- Chang, Y. K., Lee, J. W., Jeon, S. L. & Kim, M. R. 1998. A taxonomic study of the soil algae in Korea. *J. Nat. Sci. Sookmyung Women's Univ. Korea* 9:39-43.
- Chung, J. 1993. *Illustration of the freshwater algae of Korea*. Academy Publ. Co., Seoul, 496 pp.
- Chung, Y. H. 1979. The basic study for the ecology of fungi and algae for the conservation of soil environments. *Rep. Conserv. Nat.* 1:1-395.
- Crispim, C. A., Gaylarde, C. C. & Gaylarde, P. M. 2004. Biofilms on church walls in Porto Alegre, RS, Brazil, with special attention to cyanobacteria. *Int. Biodeterior. Biodegrad.* 54:121-124.
- Ghadai, A. K., Sahoo, S. & Raut, S. 2010. Agroecological survey of cyanobacterial population in paddy field soils of Gunupur. *Int. J. Agric. Sci.* 2:28-32.
- Gomez, S. R., Johansen, J. R. & Lowe, R. L. 2003. Epilithic aerial algae of Great Smoky Mountains national park. *Biologia (Bratisl.)* 58:603-615.
- Hirose, H. M., Akiyama, T., Imahori, H., Kasaki, H., Kumano, S., Kobayashi, H., Takahashi, E., Tsumura, T., Hirano, M. & Yamagishi, T. 1977. *Illustrations of the Japanese freshwater algae*. Uchidarokakugo Publishing Co., Ltd., Tokyo, 933 pp.
- Hyvert, G. 1972. *The conservation of Borobudur Temple*. Unesco, Jakarta, 172 pp.

- John, D. M., Whitton, B. A. & Brook, A. J. 2002. *The freshwater algal flora of the British Isles*. Cambridge University Press, Cambridge, 702 pp.
- Kalavathi, D. F., Uma, L. & Subramanian, G. 2001. Degradation and metabolization of the pigment: melanoidin in distillery effluent by the marine cyanobacterium *Oscillatoria boryana* BDU 92181. *Enzyme Microb. Technol.* 29:246-251.
- Kim, G. H., Klotchkova, T. A. & Suh, M. C. 2001. The effect of chemical treatments on biodeterioration of stone cultural properties. *Korean J. Environ. Biol.* 19:101-105.
- Kim, K. A., Kim, Y. J., Song, M. J., Ji, K. W., Yu, P. J. & Kim, C. W. 2007. Evaluation of water quality characteristics in the Nakdong River using multivariate analysis. *J. Korean Soc. Water Qual.* 23:814-821.
- Kim, Y. J., Kim, O. J. & Lee, O. M. 2010. The distribution of aerial algae and the assessment of biological pollution class at 8 stone cultural heritages in Korea. *J. Conserv. Sci.* 26:259-268.
- Kim, Y. J., Kim, O. J. & Lee, O. M. 2011. The community of aerial algae and the biological pollution coverage at 9 stone cultural heritages in Korea. *J. Conserv. Sci.* 27:145-154.
- Klochkova, T. A. & Kim, G. H. 2005. Ornamented resting spores of a green alga, *Chlorella* sp., collected from the stone standing buddha statue at Jungwon Miruksazi in Korea. *Algae* 20:295-298.
- Lakatos, M., Bilger, W. & Büdel, B. 2001. Carotenoid composition of terrestrial Cyanobacteria : response to natural light conditions in open rock habitats in Venezuela. *Eur. J. Phycol.* 36:367-375.
- Lamenti, G., Tiano, P. & Tomaselli, L. 2000. Biodeterioration of ornamental marble statues in the Boboli Gardens (Florence, Italy). *J. Appl. Phycol.* 12:427-433.
- Lim, A. S. & Lee, O. M. 2008a. Distribution of aerial algae and biological classes in five stone cultural properties of Korea. *Algae* 23:63-69.
- Lim, A. S. & Lee, O. M. 2008b. The distribution of aerial algae and the evaluation of algal inhabitation on five stone cultural properties in Gyeonggi-do. *Algae* 23:269-276.
- Lowe, R. L., Sherwood, A. R. & Ress, J. A. 2009. Freshwater species of *Achnanthes* Bory from Hawaii. *Diatom Res.* 24:327-340.
- National Research Institute of Cultural Heritage. 2008. *Development on evaluation technology of deterioration for conservation of stone cultural properties*. Research report. National Research Institute of Cultural Heritage, Daejeon, 652 pp.
- Naz, S., Hasan, M. U. & Shameel, M. 2004a. Biodiversity of *Oscillatoria* (Nostocophyceae, Cyanophyta) from northern areas of Pakistan. *Pak. J. Bot.* 36:503-530.
- Naz, S., Hasna, M. U. & Shameel, M. 2004b. Taxonomic study of Chroocophyceae (Cyanophyta) from northern areas of Pakistan. *Pak. J. Bot.* 36:247-281.
- Pouličková, A. & Hašler, P. 2007. Aerophytic diatoms from caves in central Moravia (Czech Republic). *Preslia* 79:185-204.
- Prescott, G. W. 1973. *Algae of the western great lakes area*. Otto Koeltz Science Publishers, Koenigstein, 660 pp.
- Prescott, G. W., Bicudo, C. E. M. & Vinyard, W. C. 1982. *A synopsis of North American Desmids. Part II. Section 4*. The University of Nebraska Press, Lincoln, NE, 358 pp.
- Prescott, G. W., Croasdale, H. T. & Vinyard, W. C. 1972. *North American flora, Series II. Part 6. Desmidiaceae*. New York Botanical Garden, New York, 37 pp.
- Prescott, G. W., Croasdale, H. T. & Vinyard, W. C. 1977. *A synopsis of North American Desmids. Part II. Desmidiaceae: Placodermae. Section 2*. The University of Nebraska Press, Lincoln, NE, 207 pp.
- Prescott, G. W., Croasdale, H. T., Vinyard, W. C. & Bicudo, C. E. M. 1981. *A synopsis of North American Desmids. Part II. Section 3*. The University of Nebraska Press, Lincoln, NE, 385 pp.
- Rai, A. N., Bergman, B. & Rasmussen, U. 2002. *Cyanobacteria in symbiosis*. Kluwer Academic Publishers, Dordrecht, 359 pp.
- Sarró, M. I., García, A. M., Rivalta, V. M., Moreno, D. A. & Arroyo, I. 2006. Biodeterioration of the Lions fountain at the Alhambra Palace, Granada (Spain). *Build. Environ.* 41:1811-1820.
- Tiwari, G. L. 1972. A study of the blue-green algae from paddy field soils of India. *Hydrobiologia* 39:335-350.
- Uher, B. 2008. Spatial distribution of cyanobacteria and algae from the tombstone in a historic cemetery in Bratislava, Slovakia. *Fottea* 9:81-92.
- Videla, H. A., Guiamet, P. S. & Gomez de Saravia, S. 2000. Biodeterioration of Mayan archaeological sites in the Yucatan Peninsula, Mexico. *Int. Biodeterior. Biodegrad.* 46:335-341.
- Wehr, J. D., & Sheath, R. G. 2003. *Freshwater algae of North America: ecology and classification*. Academic Press, San Diego, CA, 918 pp.
- West, G. S. & Fritsch, F. E. 1972. *A treatise on the British Freshwater Algae*. Cambridge University Press, Cambridge, 534 pp.