Diversity of an aerial phototrophic coating of historic buildings in the former Auschwitz II-Birkenau concentration camp

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A B S T R A C T

Aerial phototrophs colonize materials of anthropogenic origin, thus contributing to their biodeterioration. Structures preserved at the former Auschwitz II-Birkenau concentration and extermination camp show signs of degradation by cyanobacteria and algae. In order to protect the Auschwitz-Birkenau Memorial Site, diversity of aerial phototrophs growing on the historic buildings has been studied. Analyses of cyanobacterial and algal biofilms growing on various construction substrates were carried out in summer and winter. Multivariate data analyses were used to: characterize the diversity of cyanobacteria and algae growing in brick and wooden camp buildings depending on the research season, indicate preferences of cyanobacteria and algae in colonizing substrates, and to predict the environmental factor that most determines the growth of phototrophs. The biofilms were formed mainly by cyanobacteria, green algae and diatoms. The amount of cyanobacteria and algae in the biofilms was varied, which resulted from changes in climatic conditions, the type of substrate and the height at which the biofilms developed. In the summer, the ratio of cyanobacteria and algae groups was balanced, while in the winter, green algae and diatoms were dominant. Green algae showed a preference for colonizing plaster, wood and concrete, of which the walls and doors of the buildings were made. Their participation was correlated with a height gradient. Cyanobacteria and diatoms grew on bricks and soil on the floor of the buildings and temperature and relative humidity were the factors that modified their amount. Green algae were more cosmopolitan—occurred in dry places, potentially inaccessible to other organisms; therefore, they have been identified as the pioneer group in the prevailing climatic conditions.

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1. Introduction

Cyanobacteria and algae include a group of organisms characterized by a specific ecology. These are aerial phototrophs, which have developed various adaptation mechanisms, yielding the ability to colonize and grow in the terrestrial environment. They can modify the proportion of pigments in cells, which protects the photosynthetic apparatus against excessive UV radiation and produce envelope membranes that protect cells against water loss (Johansen, 2001; Żelazna-Wieczorek, 2011). These organisms grow on tree trunks, bedrock, soil (Kawecza and Eloranta, 1994; Samad and Adhikary, 2008) as well as all kinds of...
artificial substrates produced by human activities (Rindi and Guiry, 2004). Aerial cyanobacteria and algae communities develop in all climate zones (Gaylarde and Gaylarde, 2000; Samad and Adhikary, 2008). In the temperate zone, these communities are largely formed by unicellular and filamentous forms of green algae (Chlorophyta) (Rindi and Guiry, 2004; Samad and Adhikary, 2008), while in the warmer, temperate to tropical climate, by blue-green algae (Cyanobacteria) that produce various kinds of mucilaginous envelopes protecting cells from excessive drying (Crispim et al., 2004; Samad and Adhikary, 2008).

Man does not play a significant role in the spread of terrestrial algae. The cells of algae and their spores are carried by the wind (Brown et al., 1964; Barberousse et al., 2007). After reaching the substrate in good condition, they divide and grow to form various kinds of biofilms.Basically, the type of substrate does not play a decisive role in the development of natural strains, because cyanobacteria and algae are so well adapted that the growth biofilms is possible on wood, brick or concrete substrates. There are, however, trends in colonisation, which are related to the physical properties of materials such as roughness and porosity (Barberousse et al., 2007). The decisive role in the growth and development of cyanobacteria and algae is played by appropriate light conditions, temperature and humidity, which are associated largely with a distance from larger aquatic ecosystems and vegetation (Barberousse et al., 2006). Access to mineral compounds and adequate substrate pH are also important (Grbić et al., 2010). Seasonal modifications in the structure of phototrophic communities growing on substrates are due to seasonal variation in temperature and humidity (Ress and Lowe, 2013).

Terrestrial cyanobacteria and algae are pioneer organisms, which colonize habitats potentially unavailable for living organisms and transform them, allowing other groups of organisms to colonize there (Graham et al., 2009). Formation of the phototrophic biocenos, formation of the photosynthetic biofilm (Tomaselli et al., 2000). Phototrophs inhabiting anthropogenic substrates thereby contribute to their rapid biodeterioration (Tomaselli et al., 2000; Crispim and Gaylarde, 2004; Samad and Adhikary, 2008). They produce photosynthetic pigments, which change the colour of the substrates on which the cyanobacteria and algae grow. This adversely affects the aesthetic value of buildings and cultural monuments (Grbić et al., 2010; Hauer, 2010; Stupar et al., 2012). When humidity changes, the hydration and volume of algal cells are also modified, causing structural microdamages to substrates (Gorbushina, 2007; Hauer, 2010). Many phototrophs are capable of dissolving compounds contained in a substrate and penetrating into it, causing mechanical erosion (Brehm et al., 2005; Crispim and Gaylarde, 2004; Hauer, 2010). During the metabolic activity of the algal cells, various types of inorganic and organic acids are produced and algae secrete them into the external environment, causing chemical deterioration of substrates (Gaylarde and Morton, 1999; Samad and Adhikary, 2008; Stupar et al., 2012).

For the protection of buildings of historic interest, it is crucial to identify the organisms that cause biodeterioration of materials and learn their autecology. Buildings in the former Auschwitz II-Birkenau concentration and extermination camp in Brzezinka are the site of the Nazi German concentration and extermination camp Auschwitz were inscribed on the UNESCO World Heritage List in 1979. It is one of the most important symbols of the atrocities of World War II. One of the goals of the Auschwitz-Birkenau Preservation Plan is to protect the structures of the Auschwitz-Birkenau Memorial Site against biodeterioration, because signs of biological degradation caused by bacteria, fungi and algae have been observed on them. The results of research on microorganisms that cause biodegradation of historic structures are shown in Rajkowska et al. (2013) and Koziróg et al. (2014), whereas this work presents the results of the study on the diversity of terrestrial cyanobacteria and algae.

The aim of this paper is to characterize the taxonomic diversity of aerial phototrophs on the historic buildings at the former Auschwitz II-Birkenau concentration and extermination camp. The scope of the research includes the qualitative and quantitative analyses of phototrophic communities growing on various substrates in summer and winter, an analysis of the dominance of phototrophic groups depending on the season, examination of preferences in colonizing different types of substrates and characterization of the effect of temperature and relative humidity on the growth of cyanobacteria and algae. The paper also presents a research hypothesis: is it possible to specify a pioneer group among the identified phototrophs in the given climatic conditions?

2. Material and methods

2.1. Study area

The former Auschwitz II-Birkenau concentration and extermination camp in Oświęcim covers an area of about 171 hectares. Currently, there are 76 brick buildings and 22 wooden buildings (Fig. 1). The area of the former camp, where the historic housing buildings are situated, is devoid of trees and the structures are exposed to constant light radiation. The camp is surrounded by forest from the north-western side, while a watercourse runs on its south-western side. During heavy downpours, the water level rises in the watercourse, soil moisture goes up and the buildings located on the eastern side of the camp are partially flooded.

The study was conducted in ten buildings: eight brick barracks (inv. no 66, 70, 110, 113, 114, 124, 125 and 138) and two wooden barracks (inv. no 159 and 169). The barracks were in different technical conditions. Some were more damaged and damp (70, 113, 114, 124, 125, 138), while others were characterized by a better state and lower moisture content (66, 110, 159, 169) (Table 1). In places where the visual assessment showed the development of phototrophic biofilms (Fig. 2), environmental parameters were measured: air temperature and relative humidity were measured using the thermohygrometer Elmetron PWT-401 and samples were taken for phycological analysis. Samples were collected from locations inside and outside the buildings: floors, walls, foundations of buildings and doors, from various heights (from 0 to 200 cm). Biofilms were taken from mineral substrates (bricks, concrete and plaster) and organic substrates (indoor soil and wood). Samples of moss thalli were also collected from two locations around building 124, where algae grow in the macroscopic visible form, in order to check whether these sites are the source from which the algae get onto the building substrates.

2.2. Phycological analysis

Phycological material was collected during the summer (06/2012) and winter (12/2012). Biofilms of approximately 9 cm² were removed from substrates with a hard brush and placed in 4% aqueous solution of formaldehyde, in order to fix them. The moss surface was wiped with a soft brush and then the thallus was shaken in distilled water. The resulting precipitate was placed as above in the solution of formaldehyde. Samples, where diatoms were detected, were subjected to etching in a mixture of sulphuric VI and chromic VII acids (Singh et al., 2006; Żelazna-Wieczorek, 2011) to obtain silica cell walls, whose appearance is a diagnostic feature of diatoms. The qualitative analysis of samples was conducted on the basis of morphological features of the observed taxa to the genus or species level, followed by Ettl (1978, 1983), Kramer and Lange-Beratal (1986, 1988, 1991a,b), Ettl and Gärtnert (1988), Komárek and Anagnostidès (1989, 1999, 2007), Lange-Beratal (2001), Samad and Adhikary (2008), Hofmann et al. (2011), and Komárek (2013). Cyanobacteria and algae were observed with a Nikon YS 100 light microscope under magnification of 400× and 1000×.

The amount of individual taxa in samples was estimated. For this purpose, the frequencies at which different taxa occurred in 30 consecutive fields of microscopic view under a magnification of 200×, in triplicates, were observed (Kawecka and Eloranta, 1994).
2.3. Multivariate data analysis

Phototrophic communities and the effect of habitat conditions on the structure of the communities were characterized by multivariate analyses using the software CANOCO for Windows 5.0. The analysed data were different in nature—linear and unimodal. Therefore the analysis was carried out using four different techniques. A principal component analysis (PCA) and a redundancy analysis (RDA) were used for linear data, while a detrended correspondence analysis (DCA) and a canonical correspondence analysis (CCA) were used for unimodal data (Lepš and Šmilauer, 2003). The PCA and DCA techniques were used to investigate the diversity of samples based on the qualitative and quantitative analyses of algae and to show the dissimilarity of communities structure in samples depending on the research season. The CCA technique was applied to show preferences in settling on different types of substrates, while the RDA was used to indicate the impact of environmental factors on the growth of algae.

3. Results

A total of 51 cyanobacterial and algal taxa were identified in the samples, belonging to four taxonomic groups: blue–green algae (Cyanobacteria), diatoms (Bacillariophyta), chrysophytes (Chrysophyta) and green algae (Chlorophyta) (Table 2). Among the identified phototrophs, 13 taxa were connected only with bryophytes developing around barracks and their presence was not recorded in samples collected from construction substrates. Due to the high specificity of the community associated with bryophytes, the samples were excluded from multivariate analyses.

It was observed that one or two taxa were dominant in the amount of biofilm-forming cyanobacteria and algae. The communities were dominated by: cyanobacteria of the genera *Chroococcus*, *Leptolyngbya* and *Scytonema drilosiphon*; diatoms *Diadesmis contenta* and *Achnanthes minutissimum* and green algae of the genera *Chlorella* and *Apatococcus lobatus*. In the PCA analysis, the vertical ordination axis differentiated between samples from barracks in a better technical condition and samples taken from barracks in a poor state of repair (Fig. 3a–b). Algal biofilms growing on substrates in the first type of buildings were mostly formed by single-celled green algae: *A. lobatus*, *Chlorococcum infusionum*, *Chlorella vulgaris*, *Chlorella sp.* and *Coenochloris sp.* (Fig. 3a: I). The more damaged buildings were coated by the biofilms of cyanobacteria and diatoms (Fig. 3a: II). On the brick floor of brick bath buildings, 70, 113, 114, and 124, the thallus of *S. drilosiphon* strongly developed during the summer period and covered locally more than 70% of the substrate surface. In the winter, this thallus completely disappeared. The horizontal ordination axis (Fig. 3b) subsequently identified samples from the winter period. The structures of phototrophic communities emerging in the winter (W) were less diversified compared to samples from the summer (S) (Fig. 3b).

There was a seasonal change in the amount of biofilm-forming taxa. In the summer, the amount of blue–green algae, diatoms and green algae was relatively similar (Fig. 4a). However, a significant quantitative advantage of single-cell green algae and diatoms was observed in samples collected in the winter. Cyanobacteria occurred less frequently in that period (Fig. 4b).

The biofilms developed on the studied mineral substrates (bricks, concrete and plaster) and organic substrates (wood and soil inside the buildings). The CCA analysis made it possible to observe preferences of particular systematic groups of phototrophs in colonizing different substrates (Fig. 5). The vertical ordination axes divided substrates into two groups, depending on their location. The first group, including substrates such as concrete, plaster and wood, was located vertically in the buildings and was mostly inhabited by green algae. The second group, located horizontally in the buildings, included brick and soil substrates and was mostly inhabited by cyanobacteria and diatoms (Fig. 5). Among the green algae, *Trentepohlia sp.*, *Treboxia sp.*, *Coenochloris sp.*, C. *infusionum*, A. *lobatus* and green algae of the genus *Chlorella* were characteristic of concrete, plaster and brick. The analysis also identified a group exclusively associated with soil samples: *Chroococcus sp.*, *Nostoc sp.* and cyanobacteria of the genus *Leptolyngbya* (Fig. 5). Horizontal ordination axes divided substrates into mineral and organic ones, depending on their origin. However, no colonization patterns relating to this criterion were observed.

Samples from concrete, plaster and wood were taken from different heights, while those from bricks and soil were collected only from the floors of the buildings. The RDA analysis showed that the height at which biofilm develops affects the development and amount of green algae (Fig. 6). The height gradient correlated most strongly with the quantitative participation of *A. lobatus* in biofilms. Air temperature influences the development of green algae to a lesser extent. Air humidity for the species of the genus *Chlorella* is a variable that is negatively...
correlated with their quantitative participation. In the case of diatoms and cyanobacteria, temperature is a variable which differentiates the structure of the communities more strongly than air humidity (Fig. 6).

4. Summary and discussion

Thirty-eight taxa of cyanobacteria and algae growing on the historic buildings in the former Auschwitz II-Birkenau concentration and extermination camp were observed during the study. Aerial phototrophs formed biofilms on different types of building substrates. Given the relatively small size of the study area, such a taxonomic diversity of phototrophs appears to be large. In Europe, Rindi and Guiry (2004) identified only 17 taxa on concrete walls and the ground adjacent to the walls, while in France, Barberousse et al. (2006) found 47 taxa on different types of organic and mineral substrate. The study at the former Auschwitz II-Birkenau concentration camp confirms that types of substrates are important for measuring the taxonomic diversity of phototrophs.

The study of aerial phototrophs indicates that the representatives of blue-green algae (Cyanobacteria) and green algae (Chlorophyta) are the main components of communities growing on substrates in the terrestrial environment (Davey, 1988; Tomaselli et al., 2000; Gärtner and Stoyneva, 2003; Barberousse et al., 2007; Stupar et al., 2012). Diatoms (Bacillariophyta) (Ress and Lowe, 2013), chrysophytes (Chrysophyta), euglenoids (Euglenophyta) and dinoflagellates (Dinophyta) (Khaybullina et al., 2010) are less numerous and they accompany the communities. The presence of euglenophytes and dinoflagellates was not recorded in the study. Xanthophora was the only genus found of chrysophytes and it occurred in a very small number of samples collected exclusively from the wooden doors of the barracks. At the same time, there were many blue-green algae, diatoms and green algae. The proportion of their participation in the communities varied depending on the technical condition of the barracks and was subject to seasonal change. In the summer, their participation remained in relative equilibrium. Differences occurred in the case of individual samples from the barracks in a good state of repair which were better ventilated and less damp than the barracks in a poor technical condition, which were stuffy and the floor bore the signs of prolonged moisture. A. lobatus, C. vulgaris, Chlorella sp., C. infusionum, Coenochloris sp. and Trentepohlia cf. odorata were dominant in the first type of barracks. Due to a more favourable microclimate for the development of cyanobacteria and algae (smaller range of temperatures and higher humidity), cyanobacterial blooms and thalli, with a dominance of S. drilosiphon, A. lobatus, C. vulgaris, cf. odorata and Trentepohlia cf. odorata were dominant in the first type of barracks.
Diatoms were recorded in samples throughout the study period and a greater diversity of species was observed under the conditions of high humidity, which, as noted by Ress and Lowe (2013), is due to their lower adaptive capacity to over-drying. Casamatta et al. (2002) state that a lack of diatoms in dry places is a common phenomenon, but in the study these algae commonly occurred in dry places, but in the form of almost single-species cultures of D. contenta. This species is typical for terrestrial habitats. D. contenta are able to successfully develop even after little and short-term contact with water (Hofmann et al., 2011). Their presence in extremely dry habitats on the studied structures and in highly humid places, on the border of the water and air environment, where they were often observed, suggests a wide range of tolerance to humidity conditions, as confirmed by Veselá and Johansen (2009). Cyanobacteria S. drilosiphon growing on the bricks of bath barracks clearly preferred warmer and humid microclimate. When the temperature dropped below 20°C, the cyanobacteria started to die, which was accompanied by discoloration of the thallus from intense turquoise to pale yellow. This species is identified in terrestrial

![Image](https://example.com/image.png)

**Fig. 2.** Biofilms developing on the building materials in the former Auschwitz II-Birkenau concentration camp. a = biofilm on the brick floor in a brick barrack; b = biofilm on the soil in a brick barrack; c = biofilm on a patch in a brick barrack; d = biofilm on the concrete and wood of a wooden barrack [each part 1 column fitting; all 2 columns fitting].

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*The total number of samples.*
ecosystems, where it often develops on bricks. It is observed mainly in tropical climates, but at elevated temperature and humidity; it also occurs in temperate climates (Starmach, 1966; Guiry, 2013; Komárek, 2013).

Green algae (Chlorophyta) can be considered a characteristic and permanent group of aerophytic algae that occurs on the historic buildings in the former Auschwitz II-Birkenau concentration camp. Their taxonomic diversity is much smaller than that of cyanobacteria and diatoms; however, they occur more frequently than other phototrophs and their quantities are almost equal both in summer and winter. *A. lobatus*, which occurred very often and in large numbers, markedly increased their amount in the communities located above the ground, which was associated with a decrease in humidity. It is a species characteristic of terrestrial algal communities and it often develops on materials of anthropogenic origin. The occurrence of this species appears to be independent of the type of substrate, because it can be found both on a mineral substrate—granite, limestone, concrete (Tomaselli et al., 2000; Gärtner and Stoyneva, 2003; Barberousse et al., 2006)—and on an organic substrate such as wood.

Sunlight, humidity and temperature are the most significant factors in the development of natural phototrophic biofilms on building materials (Barberousse et al., 2006; Sethi et al., 2012). In the area of the former Auschwitz II-Birkenau concentration camp, cyanobacteria and algae appeared inside the barracks only in areas exposed to sunlight. Biofilms occurred both in dry and humid places and at temperatures from above 25 °C in the summer to about −6 °C in the winter. These factors did not affect the phenomenon of phototrophic colonization of substrates. Temperature and humidity were important, but from the point of view of particular groups of phototrophs. Khaybullina et al. (2010) also stress that a substrate pH is an important colonization parameter, as it mainly affects the qualitative composition of cyanobacteria and algae.

Cyanobacterial and algal preference for substrates identified in the study was related to their location. Green algae inhabited vertical substrates—walls made of wood, concrete or plaster—while cyanobacteria preferred horizontal substrates—floors made of bricks.
Barberousse et al. (2007) indicate that porosity and roughness are the most important physical characteristics of materials in terms of the rate of photorophic colonization on substrates, because they increase the ability for water absorption and retention, which then causes an increase in microhumidity. However, differences in microhumidity do not affect the weight of cyanobacteria and algae growing on structures, but modify their taxonomic composition, since the occurrence of certain species such as *Leptolyngbya foveolarum* can have a direct relationship with increased microhumidity (Barberousse et al., 2006). In the study, air humidity represented an environmental factor, which affected the growth of phototrophs to a lesser extent than temperature. During the study, relative humidity was a parameter that did not enter the succession in substrates in unfavourable conditions after snow melting (Davey, 1988; Barberousse et al., 2006). The succession suggests that this group of organisms is the most widespread and shows pioneer tendencies in colonizing building structures. It is green algae that begin the succession in substrates in unfavourable conditions after snow melting (Davey, 1988; Barberousse et al., 2006). The succession of aerial phototrophic groups is different for warm and tropical climates, where cyanobacteria form the main biomass in communities and are the first to colonize an inaccessible environment (Mulec et al., 2008; Ress and Lowe, 2013). It can therefore be concluded that under the conditions of higher temperature and humidity, cyanobacteria show pioneer tendencies in settling in microhabitats, while green algae are the pioneer group in temperate and cold climates as they are adapted to drier conditions.

The pioneer green algae indicated in the study are a biological degradative factor, which primarily affects the aesthetic qualities of buildings. The activity of green algae is less degradative than that of cyanobacteria as the latter change the hydration of cells and their membranes, penetrate the surfaces of substrates (even if they are coated with a layer of protective paint) and thus damage them (Hauer, 2010). For this reason, no study has been conducted so far to identify the role and examine the degradative activity of green algae.

In further studies of aerial phototrophs growing on the buildings in the former Auschwitz II-Birkenau concentration camp, investigation is planned into the effect of different compounds on the development of biofilms. The study will allow for the selection of appropriate methods to control and prevent degradation caused by autotrophic organisms in order to protect the monuments of the Auschwitz-Birkenau State Museum in Oświęcim.

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References


Fig. 6. The RDA ordination biplot displaying the influence of environmental variables on the presence of phototrophs [1 column fitting].


