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Application of 2D FFT Spectra and Correlation-Spectral Analysis to Assess Micro-Meteorological and Microbiological Weathering the Pavement Lights, Sidewalk Prisms and Other Anidolic Optics in Water

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Abstract

Pavement lights, also known as sidewalk prisms or anidolic optics, play a crucial role in urban infrastructure by providing natural illumination to underground spaces while enhancing pedestrian safety. However, the effective performance and longevity of these lighting systems are heavily dependent on their resistance to environmental factors, particularly moisture and corrosion. In civil engineering and hydraulic engineering, the implications of inadequate moisture protection are profound. Pavement lights are often installed in environments exposed to rain, snow, and other forms of precipitation. Without proper sealing and corrosion resistance, these fixtures can suffer from water infiltration, leading to electrical failures, rust, and the degradation of materials. To ensure durability and reliability, it is imperative that pavement lights comply with established protection standards, such as IP67 or IP68. Adhering to these standards is essential for preventing corrosion and biological weathering, which can severely compromise the structural integrity and functionality of pavement lights. Biological weathering, which can occur when moisture facilitates the growth of mold or algae on or within the lighting fixtures, further exacerbates the problem. Firstly, we offer a complete overview of the mechanisms of effects accompanying the degradation of glass in such pavement lamps, and secondly, we offer methods for analysing the behaviour of lamps based on 2D FFT and correlation-spectral analysis methods, including in the time-resolved ones.

Keywords: Pavement Lights; Sidewalk Prisms; Anidolic Optics; Anidolic Lightings; Biogenic Weathering; Geochemical Weathering; Correlation-Spectral Analysis; 2D Fourier Spectra; Hydraulic Engineering; Civil Engineering; Glass Chemistry.

Introduction

A general problem of the design of existing outdoor lighting systems, including built-in systems of architectural and artistic lighting of buildings (and especially those whose glass parts are at the ground or sidewalk level) is the problem of degradation of the transparent glass and/or polymer (either aesthetic or protective) coating, due to the condensate formation and leakage, which first leads to a decrease in the efficiency and a change in the lighting pattern, and then to the failure of the lighter. Together with the degradation of the transparent part of the lighting device (which most actively occurs in the case of operation in a harsh climate with high gradients of the climatic parameters) degradation of the metal structures and electrical connects or fittings also occurs, but, as a rule, attention is paid to them only at the pronounced stages of corrosion and geochemical weathering, since before the critical point of these stages they either do not affect, or have less influence on the direct lighting indicators.

The main technical reason for the failure of conventional luminaires is often considered to be the non-compliance of the IP67 standard with the climatic conditions of their operation in northern countries. This is true from the corrosimetric point of view, and attempts are being made all over the world to optimize the classes of metal materials for such luminaires, as well as many other structures that comply with IP67 standards. For both luminaires and other electrical systems, special emphasis is maed on optimizing the materials of power supply circuits, in particular - connectors and metal boxes in which the luminaire is mounted. Due to the "technical fashion", in-depth development within the IP67 standard is carried out for mobile devices, in particular, those for biomedical/telemedicine purposes, even where this protection class is not required [1-7]. It is noteworthy that the glass degradation or weathering is not considered from the point of view of IP67 standard as a key process for the failure of the luminaire under the operation conditions. When fixing the cause of failure of a lighting device, usually only degradation or wear of the conductive parts by thermal cycling is fixed. However, in the case of a device located in a natural environment, it is not reasonable to reduce the diagnosis to an epicrisis of the cause of the terminal stage, since the deterioration of the lamp condition, the efficiency of its operation, begins long before its complete inoperability (due to the loss of the optical properties of the glass transmitting light).

Therefore, it is necessary to move from the statement of the phenomenology of the last stage to a physically consistent, and, ideally, physical-chemical consideration of the set of phenomena that entailed the initial decrease in the qualimetric characteristics of the luminaire, and then to their stage correlation with the pre-terminal processes in its electrical circuit. Since the target function of the built-in luminaire is the light supply and its angular concentration within the large solid angles due to the optimal scattering in accordance with the geometry, it is logical, first of all, to analyse the processes affecting the optical transmission and scattering of radiation passing through the glass of the illuminator, as the earliest superficially perceptible descriptors of the degradation process of the latter.

According to the IP criteria map of the protection degree of luminaires from the environment, the first digit nomenclature includes the limit description of the granulometric composition (dust/abrasives/particles and solids of the macroscopic sizes from 6 to 1), which quite accurately meets the real operating conditions of the luminaire (excluding special issues of the material resistance), but the second digit is not so well annotated. A complete protection of the optical and conducting parts of the luminaire is not limited to the protection from waves or jets at different angles, as well as protection during temporary or complete immersion in water. From the physicochemical positions, temperature, pressure, ionic strength of the medium, specific electrical conductivity, the presence/absence of surfactants, electrochemical potential in relation to the metal surfaces, wettability (hydrophilicity/hydrophobicity) of the surfaces, condensation (not limited to measuring the dew point), biocorrosion, and gradient (i.e. reaction-diffusion) characteristics of the weathering effect should also be taken into account. Therefore, a lamp formally manufactured in accordance with the requirements of the protection standards (IP67 or even IP68) is, in fact, defenceless against the geochemistry and hydrochemistry of the surrounding environment, which changes depending on the time of day and season.

The first criterion of this "defencelessness" visible to the user is condensation on the glass and, as a consequence of this humidification, the formation of geochemical deposits or biofilms on the inner surface. Moisture condensation on the glass surface leads to the droplet formation and dispersed patterns that scatter light [8], preventing energy-efficient lighting [9]. Depending on the hydrophilicity/hydrophobicity of the "transparent" surface (which is the carrier of the pattern with condensate from the point of view of optics) and characterized by different contact angles of the drops on the surface, condensation is different for different glass and polymer materials [10]. In particular, it differs significantly in the ordinary glass and glass with an antireflective or biocidal coating. The same effect is characteristic of the greenhouses/hotbeds [11], where the excess condensate and heat, as a rule, leads to the progression of parasitic, including fungal, microflora. As is known from classical physical chemistry, similar condensation on the surfaces of glass and similar materials is characteristic of gases and/or vapors [12], therefore the understanding of corrosion and condensation weathering in the natural atmosphere can be deepened from the reaction-diffusion positions.

Despite the long (more than a century-long) history of studying condensation on glass, which began in the second half of the 19th century, in the works of R. Bunsen [13] (known to the lighting engineers as the author of the Bunsen burner), the study of condensation for all glasses relevant to the lighting engineering has not yet been carried out. A number of authors, starting from 1907 [14], consider the "condensate pattern" formation as a phase transition regulated by the type of surface and its inhomogeneities. However, unfortunately, this concept has not received development, predicting the shape or topology of the pattern based on the nature of the glass and environmental conditions, despite the availability of the computational approaches, starting with CALPHAD (popular in the 1980s and claiming even astronomical scales of the substance condensation [15]), and ending with the multiphysical COMSOL models, which also reproduce the condensation processes [16]. Studies of moisture condensation on the surface of glass of different dimensions (from two-dimensional surfaces of three-dimensional objects to one-dimensional glass wool and model-zero-dimensional dispersed granulates) have been going on for more than a century [17,18], but the influence of the condensate morphology/topology on the transmittance of the glass of lamps (including the so-called anidolic "waveguide" and their modern Fiber-optic light-guide modifications) not only has not been solved, but, in fact, has not been posed.

The studies of condensation energy on the surface of metals, glasses, and other substrates have been separately conducted since the 1950s, more than half a century ago [19], and the effect of the emission (outflow) of the metal corrosion products (formed after moisture condensation on it) on further condensation of

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moisture on the surface of glass or polymer coating in contact with it has not been studied to date for the natural operating conditions of the built-in luminaires. Unfortunately, effectively studying complex condensation processes in exotic conditions (for example, capillary condensation on high-temperature porous glasses, in porous glass membranes [20,21], including for non-aqueous solvents), we often miss interesting and complex processes in simple condensation conditions, occurring on glass in the natural environment upon "thermocycling". Physical chemistry of the above phenomena favors defectoscopic registration of the results upon completion of the destruction process, which appears to be separated from the condensation process in the cause-and-effect relationship schemes, since it is easier to study condensation in glass cracks than its degradation upon condensation leading to the emergence of such cracks [22]. The study of condensation phenomena and patterns depending on temperature and baric gradients is carried out within the boundary conditions selected ad hoc (for example, capillary tubes [23]), while condensation on a planar surface in the natural geochemical environment, which is much more often observed, remains outside the scope of study, since it is mistakenly considered to be an "old and well-studied problem". The few works that could serve to resolve the problem posed in this paper considered the outer glass surface [24], while the hanging drop approximation is more suitable for studying condensation patterns on the inner glass surface (above the lamp) [25,26]. The most empirically close works of our Chinese colleagues, who studied condensation on a thermodynamically nonequilibrium interface, appealed to the forced cooling, which is usually absent in the conventional lamps [27]. In this regard, a full-fledged analysis of the periodic patterns of moisture condensation on glass (within the approximations adequate to the requirements of lighting engineering) has not yet been carried out (the only exception in terms of 3D visualization of condensation patterns is the work [28]).

Therefore, in this paper we propose an alternative approach for measurement and evaluation of the quality of condensation patterns from the standpoint of applied lighting engineering (considering the microstructure geometry and dynamics/kinetics of condensation [29] which affects the light scattering, sometimes improving, rather than worsening, the lighting effect and surface visualization [30,31]). From the standpoint of diffraction and microprism optics, which have recently been frequently used to improve the quality of lighting [32,33], condensates can synergistically affect their own diffraction and microprism masks (in the surface layer of the glass transparent of the lumonaire), due to which single glass hydrophobization [34], which prevents the condensate formation, is not enough to improve the quality of lighting. This does not remove either the problem of the climate impact and IP6x regulation, or the economic problems, but it allows to reproduce some natural phenomena that contribute to the formation of the effective optical structures and surfaces under various conditions of the native environment, which corresponds to the main principles of "geonics" and "geomimetics" [35] developed similarly to the conceptual ideas of "bionics" or "biomimetics" which used to be widely applied in lighting engineering earlier [36,37].

The second criterion of non-fatal damage to the glass surface is the optical effect of biofilm formation on its surface, which correlates with the same weather and phenological conditions as the formation of condensate patterns. A biofilm often grows along the concentration gradient of the elements accumulated during periodic condensate evaporation and the emergence of new drips. Humid conditions that favor condensation, together with the temperature differences increasing the surface degradation, are optimal conditions for the growth of the microorganism cultures, and microcracks, from the standpoint of conventional "capillary chemistry" [38,39], contribute to the formation of new nanophases from the drip materials and favor some contact (cyto)physiological processes in the cell cultures developing in the material. The first data on the cytologically-relevant capillary-chemical phenomena refer to the works of G. Freundlich - the author of the adsorption isotherm [40]. Despite the skepticism of a number of the light engineering specialists regarding the role of microorganisms/microbial biofilms in the deterioration of the lighting quality, this factor cannot be neglected, since the elements of biofilms with microorganisms of various biological taxonomies, as a rule, accompany the structure formation on the lamp surface, which are usually considered as drips, condensates, and the products of evaporite sedimentation and quasi-template biomineralization on the glass surface.

In the most general microbiological context, biofilms on glass are formed by dozens of genera of microorganisms, such as Salmonella [41], Pseudomonas [42], Aeromonas [43,44], Listeria [45], Streptococcus [46], etc. However, for the natural conditions that do not imply the presence of pure cultures, but imply the presence of microecological links between the contaminating organisms and those interacting with them, it should be taken into account that some green algae [47] (Scenedesmus) and fungi [48] (genus Candida) can also participate in the biofilm formation in contact with glass. The biofilm formation is as fatal as condensation, since it can occur both on the seals (including the most resistant Teflon ones [49]) and on the metal parts which are in contact with the film zone, and therefore contaminated by it [50] at the surfaces with different temperature. The metabolic chemistry of the biofilm microorganisms can be different, which will affect the film adhesion [51], but it is extremely difficult to achieve such a chemical environment that is strictly negative for the biofilm growth.

Mineralization/local salinization of the environment does not hinder, but often promotes effective trophism and development of the biofilms [52], especially if it acts synergistically with the chemoautotrophy of these species in the given environmental and climate conditions. The key redox characteristics (oxygen concentration and pH), along with the changes in specific conductivity in terms of a single salt (usually NaCl, although, really,

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the medium salinity is provided by many different ions), vary widely at different stages of the biofilm development [53,54], due to which they are not informative outside the phenological context of the film development. The active biofilm growth in an aquatic environment, corresponding to the eutrophication stage of a reservoir with the increasing content of the nitrogen compounds, occurs after biomass accumulation of the microorganisms' producing biofilms on the glass surface [55]. Therefore, without a stage-by-stage understanding of the mechanisms of the biofilm formation on a non-imaging optical or a light-transmitting glass of the illuminators/portholes/pavement lights (vault lights, floor lights) or sidewalk prisms, it is impossible to predict the effect of a biofilm on the luminous flux, even with the known surrounding environmental parameters.

The lack of understanding of the mechanisms and stages of microbiological and bacterial fouling does not allow one to effectively combat it. General experimental studies with the predictable conclusions (for example, on the need to combat the water hardness at the level of its source, including selectively for calcium [56]) cannot be used in architectural lighting conditions, since it is impossible to vary the precipitation hardness by the known methods, and the buildings themselves, in terms of materials and binders, are the sources of calcium washed out during geo-/hydrochemical weathering (not differing in this aspect from the calcium-containing bone and dental tissues, which do not prevent the biofilm formation on their surface [57]). Therefore, limiting ourselves to separating mature biofilms from the glass substrate on the lamp surface (using either abrasives or detergents) [58,59] and performing simple disinfection and deterioration of the glass surface [60,61], in real practice we will constantly face the physicochemical cause of the bacterial contamination and film growth, without being able to combat it, symptomatically carrying out only the simplest aesthetic renewal of the corresponding lighting system.

In fact, even at the normal temperatures-from the room one to the human's body temperature [62,63]-not to mention regular daily ("circadian") thermal cycling, the adaptability of biofilms to the disinfection measures can increase. Necessary and sufficient (at the level of the glass material) measures for the biofilm growth inhibition are economically unprofitable nuclear-chemical and nano chemical methods (such as irradiation using Marx or Van der Graaff generators with particle beams with an energy up to 6-8 MeV with the introduction of the ultrafine particles of heavy metals into the glass matrix) [64]. The currently available alternative methods for combating biofilms using modification of the glass structure are focused on a strictly narrow range of medical devices and limited taxa of the biofilm forming microorganisms- [65,66]. Examples are photocurable glass ionomer cements [67,68] or glass-containing composites, the optical properties of which, as well as the properties of illuminating glass, are strongly affected by the biofilms [69]. But their use, as a rule, is associated with the in situ selection for a specific category of films, which corresponds to different bactericidal agents introduced into the composition, often expensive ones (from the relatively cheap, but unstable on the time scale of operation of the street glass chlorhexidine [70-72], to the stable, but irrational for a mass introduction silver ions [73-75]), which excludes their use in the composition of the mass-produced glass, where it is usually impossible to predict the taxonomic composition of the fouling biofilm. The release of many ions that can participate in the antimicrobial activity of the composite (such as fluoride ion [76] or zinc [77]) can cause "chain ecological reactions" that exceed the negative effect of biofilms on the glass. For this reason, selective pretreatment of the glass surface, which provides bactericidal and fungicidal preventive effects (for example, against Candida fungi [78]) [79] is becoming increasingly popular. Therefore, it is necessary to look for the methods and approaches in a simpler physicochemical field and in the optimization of the lighting modes consistent with the properties of this type of biofilms (it is quite obvious that for the biofilms formed by the algae-containing microbial communities, by definition, possessing light sensitivity due to the presence of photosynthetic pigments, the requirements for the irradiation mode are quite different from those for non-photosynthetic microbial communities that perceive only the thermal component of irradiation without spectral selectivity in the visible range) and spectrochemical or photochemical properties of the glass itself, achieved during its processing, including at the stage of the glass production.

However, in order to select an effective strategy for influencing the material or coating spontaneously formed on it in certain (bio) geochemical conditions, first of all, it is necessary to understand what type of contamination or structural defects of the glass surface we are faced with, that is, to have a quantitative "fingerprint" of its current state (without extracting it from the operation conditions), which contains information that can be compared with a database of different states of the glass surface under natural conditions in order to identify its belonging to a particular state and predict the corresponding risk group of the material in the case of continued exposure under current conditions. Due to the need for unification, distinguishing between mechanical, chemical, and biological defects of glass, this fingerprint cannot be chemical (as the specific markers on biofilms [80-82]), but must be structural, identifying the nature of the defect by the surface structure. For example, the result of a texture analysis can be proposed as an identification descriptor, which can be implemented in the simplest form of a two-dimensional Fourier spectrum [83]. In the methodological part of this paper, we proceed from the universality of this 2D textural approach, appealing to the integral spatial characteristics, calculated directly on the basis of the 2D Fourier spectrum.

Methods

The measurements can be carried out in three main versions:

- In real time using a tablet or a laptop with a webcam

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placed on a movable table with wheels to ensure parallelism to the ground, which is necessary during imaging (for example, medical procedure wheeled tables with removable shelves can be used for this purpose, such as SI-03/1, SIP-2S, SP 3G and their foreign analogues).

➢ In the telemetric version of the real time mode, when the video stream from an autonomous camera is transmitted via a radio frequency channel to a stationary laptop without moving it (this is an optimal mode for a rainy or frosty weather, since it prevents the measuring complex from damaging).

➢ In the mobile version when registration is carried out by a camera built into a camera phone with a memory card, and a real-time operation mode is not required, although it can be achieved by ensuring data transmission via some Internet messenger with the real-time processing software installed on the receiving laptop/stationary PC.

In all the real-time versions data processing is performed using QAVIS software (developed by A.A. Goncharov and V.K. Fishchenko from the Pacific Oceanological Institute FEB RAS), which provides direct visualization of 2D Fourier spectra and calculation of the integral frequency characteristics and integral spatial characteristics from them, with the color highlighting of the remarkable periods-descriptors of the order of the structure studied. However, the computing capabilities of this software are optimal for the coating qualimetry, but not for its metrological assessment, for which another program developed by the same authors should be used-KSAImage, which allows calculating periodograms from the images, performing measurements in spectra, approximating integral frequency characteristics using the least square method with various theoretical dependences of spectra, which are a superposition of the spectral densities of the first and second types, analyzing the spectra anisotropy based on the integral spatial characteristics, performing correlation analysis and deposition of spectra and other calculated characteristics of the images to various databases for AI/machine learning based identification.

For ensuring comparability of the measurement results, one should compare only data obtained using the sensors with identical resolvometric characteristics. Therefore, a sufficiently correct comparison can be achieved within one measurement option with the same sensor type. However, this is typical, as a rule, for the “metrological” interpretation of correlation-spectral analysis (preformed using KSAImage), and not for its evaluative “qualimetric” version (performeed using QAVIS).

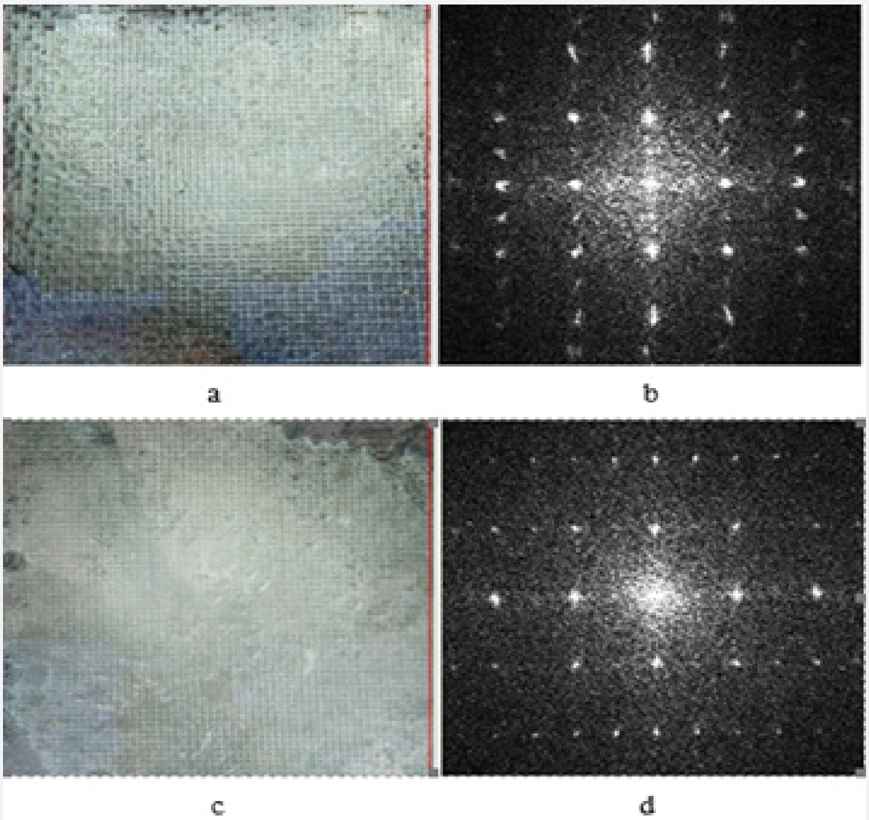

Figure 1: Photographic images (a, c) and 2D FFT patterns (b, d): A completely fresh coating with initial condensation level: despite the presence of condensate, all the order signatures are preserved (a, b). Disturbances of the initially homogenous surface lead to a partial attenuation of some reflections (c, d).

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Results

Full dataset "Weathering and biodegradation of the surface/coating of light fixtures near the State Hermitage Museum" (DOC1: Fourier spectra; DOC2: Integral Spatial Characteristics & Integral Frequency Characteristics; DOC3: Statistical characteristics and histograms) was deposited in the "Knowledge Network for Biocomplexity" of the National Center for Ecological Analysis and Synthesis (NCEAS, Santa Barbara, CA) [DOI: 10.5063/F1FJ2F3G]. Experimental results shown below were obtained using mobile camera-phone image recordings/imaging (without additional camera leveling with an accuracy exceeding the accuracy of the built-in magnetometer/gyroscope of the phone), with the primary qualimetric processing using QAVIS software, which recorded 2D Fourier spectra (Figure 1-3).

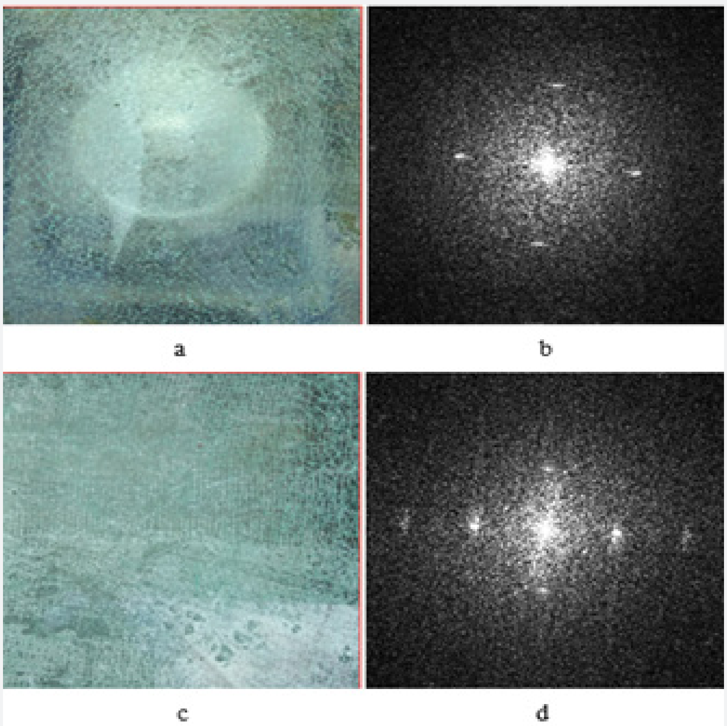

Figure 2: Photographic images (a, c) and 2D FFT patterns (b, d): Sometimes, when the surace if destroyed, its own cracking / mechanical reticulation is formed, but its regularity is much less pronounced than in the case of the original grid (a, b). Superposition of the oriented reticulation and the coating's own structure with the original grid - the ordering is preserved along one axis and the symmetry changes are detected on 2D FFT patterns (c, d).

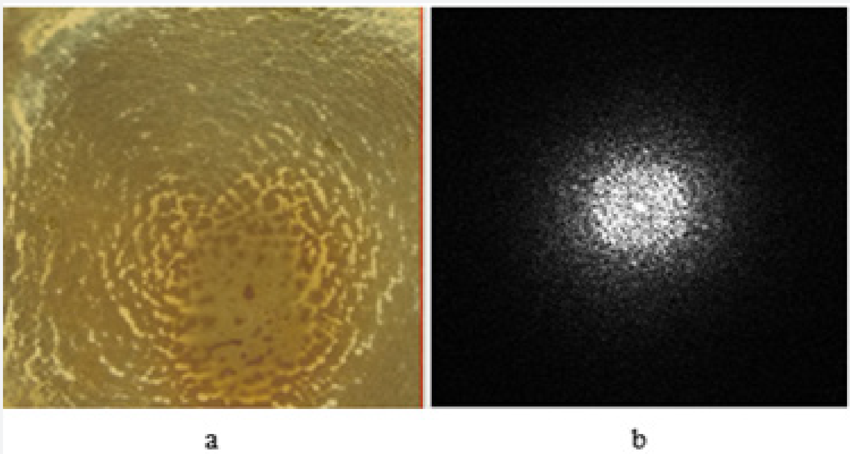

Figure 3: Photographic images (a) and 2D FFT patterns (b): Condensates are often formed within a concentric symmetry (as the Liesegang rings). Then the elements of concentric symmetry will also be detected in the biofilms or geochemical layers on the glass surface. A characteristic descriptor in this case is the "ring around the point / spot of the center".

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Discussion

As can be seen from the above data, using physicochemical approaches proposed, solution of the problems of detecting and preventing biological fouling of glass can revive interest in the anidolic optics, which has significantly decreased recently [84-90] mostly due to the unresolved climatic problems [91]. In our opinion, this monitoring solution will be especially relevant for the tropical and subtropical conditions [92-95], including the regions with regular rainy seasons, as well as for the climates with contrasting temperature and humidity conditions. If you install a lamp into the ground, and after some time condensation appears in it, the lamp leaks and fails. This happens because most street lamps currently available in the market comply only with the IP67 protection standard. This standard guarantees the lamp operation only with a short-term immersion in water and does not guarantee its operation in the snow/ice. In contrasting climates with the ice formation (Finland, Norway, Russia in the Palearctic latitudes, Iceland, Greenland, Spitsbergen, Alaska, etc.) ground lamps must operate in the frozen ground in winter, buried into the frozen soil, and in spring and autumn-fully immersed in water, therefore the IP67 standard is obviously not enough for such extreme operation conditions [96-102]. Of particular importance will be a synchronous solution for monitoring and preventing physical condensation (as a well-known phenomenon studied since the 19th century [103]) and microbiological degradation and biofouling activity caused by the condensed moisture (formation of physicochemically active biofilms degrading the lamp material on the glass surface), which can be prevented at an early stage, and the glass surface can be recycled for further use upon the regular cleaning [104]. All the phenomena described above become controllable when using the QAVIS real-time software [105-109].

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