EVALUATING THE USABILITY OF BIOLUMINESCENCE IN BUILDING INTERIORS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ÖZGE DEMİRCİ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

JUNE 2022

Approval of the thesis:

EVALUATING THE USABILITY OF BIOLUMINESCENCE IN BUILDING INTERIORS

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ABSTRACT

EVALUATING THE USABILITY OF BIOLUMINESCENCE IN BUILDING INTERIORS

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Master of Science, Building Science in Architecture
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June 2022, 138 pages

Light is an essential factor in the built environment. Lighting devices consume a significant part of electricity today, and fossil fuels are still the first energy source for global electricity production. This situation causes high CO_2 emissions and climate change, as well as a considerable amount of depletion in non-renewable energy sources. For this reason, converging to alternative renewable energy sources becomes essential. Being one of the alternative energy sources, microalgae have recently gained importance around the world. Algae is mainly cultivated for biomass production, food, fertilizer, and biological sensors purposes. However, bioluminescence features of algae have not gathered much attention, even though bioluminescent algae can be a promising lighting source for the built environment. Likewise, bioluminescent bacteria have been used for years in numerous fields, but their use in architecture is relatively new. In this scope, this study aims to examine bioluminescent light, its properties, and its potential as a light source for building interiors. To this end, a residential apartment building was selected and lighting measurements were conducted. Afterwards, a study was prepared via lighting

simulations integrating bioluminescent light, and this study presents the results of the integration of bioluminescent light in the selected building interiors.

Keywords: Bioluminescent Light, Bioluminescent Algae, Bioluminescent Bacteria, Light Production, Interior Lighting

ÖZ

BİNA İÇ MEKÂNLARINDA BİYOLÜMİNESANS KULLANIMININ DEĞERLENDİRİLMESİ

Demirci, Özge
Yüksek Lisans, Yapı Bilimleri, Mimarlık
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Haziran 2022, 138 sayfa

Işık, yapılı çevre için önemli bir faktördür. Işıklandırma bugün, küresel elektrik tüketiminin büyük bir bölümünü oluşturur ve dünya çapında elektrik üretimi günümüzde hala öncelikle fosil yakıt tüketimine bağlıdır. Bu durum yüksek CO_2 emisyonuna, küresel ısınmaya ve yenilenemeyen enerji kaynaklarının hızlı bir şekilde tükenmesine neden olmaktadır. Bu nedenle, alternatif yenilenebilir enerjiler büyük önem arz etmektedir. Algler, yenilenebilir enerji kaynaklarından biri olarak son zamanlarda dünyada ilgi çekmektedir. Daha çok biyoyakıt üretimi, ek besin kaynağı, gübre ve su kirliliği için biyolojik sensor olarak kullanılan alglerin biolüminesant ışık üretim özellikleri yapılı çevre için yüksek potansiyele sahip olmasına rağmen, bu konuda yeterli ilgi ve çalışma yoktur. Benzer şekilde, biolüminesant bakteriler yıllardır birçok alanda kullanılmaktadır, ancak mimaride kullanımları nispeten yenidir. Bu kapsamda bu çalışma, biolüminesant ışığın özelliklerini ve bina iç mekânlarında bir ışık kaynağı olarak kullanım potansiyellerini incelemeyi amaçlamaktadır. Bu amaçla, bir konut mekânı seçilmiş ve aydınlatma ölçümleri yapılmıştır. Daha sonra aydınlatma simülasyonları ile biolüminesant ışığın uygulandığı bir çalışma hazırlanmıştır ve bu çalışma,

biolüminesant ışığın seçilen bina iç mekânlarına entegrasyonunun sonuçlarını sunmaktadır.

Anahtar Kelimeler: Biolüminesant Işık, Biolüminesant Algler, Biolüminesant Bakteriler, Işık Üretimi, İç Mekân Aydınlatma

Dedicated to my dear parents, Canel Demirci and Recep Demirci

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my supervisor Prof. Dr. Soofia Tahira Elias Ozkan, for her guidance, and to the jury members for their time and valuable comments.

I would also like to thank my family for their support, love, and encouragement. Their presence gave me motivation for this study. Their support made me finish this research.

Moreover, I would like to state my appreciation to all people who helped me complete this research by sharing their knowledge.

Additionally, I would like to thank my friends for their support and help when I needed it.

Lastly, I would like to present my gratitude to all my instructors for their efforts on me during my master's education.

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CHAPTER 1

INTRODUCTION

This study focuses on bioluminescent light and its simulation for usability in building interiors. In this chapter, the argument, aim and objectives, and the procedure of the study are presented. The chapter finishes with the disposition of the following chapters.

1.1 Argument

Nature has always been fascinating for human beings. By studying nature, architects, designers, and engineers gained inspiration from different phenomena for their projects that have never been done before. Various light forms of nature such as sunlight, moonlight, phosphorescence and bioluminescence are examples of events that inspired people for years due to their remarkable effects on people's perceptions.

Being an important factor for visualizing the built environment, light and lighting sources are necessary. However, almost all lighting devices in the built environment consume energy derived from burning fossil fuels that contribute to high CO_2 emissions, climate change and depletion of non-renewable energy sources. Having been used for hundreds of years, fossil fuels have reached their limits, and nature has started to react with changes and depletion. Energy demand is still increasing day by day and fossil fuels will not be around anymore in the future. For that reason, converging to renewable energy sources and searching for alternative ones for our built environment have become one of the priorities. At this point, design and architecture disciplines need to extract knowledge from the biological world to improve the lives of humans.

Microalgae have different areas of use. They have been cultivated for biomass, food, fertilizer and biological sensor purposes for years and they are known to reduce greenhouse gas emissions in terms of CO_2 absorption. More than 300 years ago, algae were started cultivating primarily for food and medical purposes. The first mention of algae as a fuel source goes back to the 1950s, and with the energy crisis in the 1970s, more and more research was done related to the potential of algae as a biofuel source. In the mid-80s, tests were expanded and many innovations were carried out in algae biofuel production and wastewater processing (Elmeligy & Elhassan, 2019). In architecture, they have applications primarily as biomass sources in photobioreactors. On the other hand, the usage of bioluminescent ones of algae, which are classified as dinoflagellates, have gained attention only recently. Unlike the examination of microalgae species for biomass and biofuel production as renewable energy, the bioluminescence property of microalgae is an area in which researchers show less interest. Similarly, bioluminescent bacteria and the light produced by them have a number of applications in environmental, pharmaceuticals, food, agriculture and forensic fields (Cevenini, Calabretta, Calabria, Roda & Michelini, 2016). However, their use in architecture is relatively new. For that reason, there are not enough studies related to that topic. In addition to that, most existing studies do not have comprehensive simulations related to bioluminescence and its usability, especially in interior spaces.

Biologists and oceanographers have studied bioluminescence for years, however, it is relatively new for designers and because of that, it is an area that hosts many potentials, possibilities, and design opportunities to discover for architects. As one of the opportunities, it is argued that bioluminescent lighting has the potential to be used in the built environment as a light source.

1.2 Aim and Objectives

Recent studies showed that bioluminescence offers many opportunities and solutions to different fields. In architecture and design, there are studies and projects to

understand the phenomenon and its possible utilization for the built environment, but more studies are needed on simulations of the bioluminescent light and its usage in the building interiors. Therefore, the aim of this study is to investigate this new research topic and to evaluate the bioluminescence for use in building interiors. For this aim, the following objectives were described.

- To identify the appropriate bioluminescent algae and bioluminescent bacteria species for bioluminescent lighting in architecture from previous research,
- To determine the amount of light in building interiors with conventional light sources and with the integration of bioluminescent lighting,
- To visualize bioluminescent light in spaces with simulations consisting of data derived from previous works,
- To evaluate the usability of bioluminescent light instead of conventional light sources in building interiors.

1.3 Procedure

In this study, the first phase is a literature review to have comprehensive knowledge about algae and bacterial bioluminescence, and their use in architecture. Necessary information was collected related to appropriate species, bioluminescent light characteristics of algae and bacteria, previously proposed works and lighting design, which guides through simulations.

In the second phase, a case study building was selected, which is located in a residential area in Ankara. Light measurements in an apartment indoors were done with a lux meter every hour for 24 hours. The information and collected data from measurements were interpreted. Simulations were done to evaluate illuminance values before and after the utilization of bioluminescence.

The third phase includes results, scenarios and visuals of bioluminescence integration. Discussion of the data and the results obtained from the simulations and

measurements were made. Lastly, the study was evaluated, and the conclusions were presented.

1.4 Disposition

This research consists of five chapters.

The first chapter introduces the topic and indicates the arguments, aim and objectives with the procedure of the study and disposition of the following chapters.

In the second chapter, a literature review is presented for a better understanding of the bioluminescence phenomenon, bioluminescent light from algae and bacteria. Case studies were also shown in the literature review and information about interior lighting design is given.

The third chapter presents the material and method of this study.

The fourth chapter gives the results and presents the analysis. It focuses on the evaluation of the lighting measurements and simulation results.

The final chapter is the conclusion of this study.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a literature review starting with bioluminescence phenomena, the bioluminescence properties of algae and bacteria. Afterwards, current applications of algae and bioluminescent bacteria are examined. After the examination, possible implications of bioluminescent algae and bioluminescent bacteria in the architecture field are reviewed, and information related to lighting design is given. Case studies on previous projects, studies, biological light sources and installation were presented after lighting design. Lastly, a critical analysis of the literature is presented at the end of this chapter.

2.1 Bioluminescence

Bioluminescence is a widespread phenomenon defined as the biological production and emission of light by living organisms. The natural reaction requires luciferin protein and luciferase enzyme reaction with oxygen and ATP (adenosine triphosphate) for the energy for the response. When luciferin is oxidized with the help of luciferase, the emission of photons generally occurs in the form of a blue flashlight in dinoflagellates. The wavelength of this light is approximately 475 nm (Valiadi & Iglesias-Rodriguez, 2013).

In nature, there are different bioluminescent organisms such as bacteria, unicellular algae, coelenterates, beetles and fishes. Bioluminescent organisms are very abundant, especially in the marine environment. From fishes to bacteria, there are many bioluminescent species in oceans whose luminescence is significant to the human eye. Radiolarians, bioluminescent ostracods, copepods, almost all species of euphausiids and some species of cnidarians, ctenophores, pelagic tunicates play

substantial roles in this pelagic visual environment of the oceans. (Widder, 2002). Luminescent fishes and crustaceans dominate the light emitters in marine environment in terms of biomass, while dinoflagellates and bioluminescent bacteria dominate in abundance (Widder, 2010). Dinoflagellates are reported to be the most omnipresent bioluminescent protists even though more than 30 species of bacteria have been discovered as bioluminescent so far which belongs to *Gammaproteobacteria* subclass (Dunlap, 2014). The most well-known bioluminescent creature of the marine environment are dinoflagellates because of occurring in very high abundance, being mostly autotrophic and having high growth rates; it can be said that dinoflagellates attract most of the attention and they are mostly responsible for bioluminescence in oceans.

2.1.1 Dinoflagellate Bioluminescence

In the oceans, when there is a sudden increase in nutrients, algae bloom occurs and can be observed in some bays. When the algae are disturbed, they start to glow. It is more vivid when the algae blooms make the waves glow (Figure 2.1), and it is called red tide. This phenomenon is created by the dinoflagellates. Most red tides are not harmful to humans, it is possible to swim with these creatures. However, some red tides can be harmful, especially the ones created by *Lingulodinium polyedrum* (Amezcua, 2021).

Figure 2.1. Waves in the ocean with bioluminescence of Lingulodinium polyedrum in San Diego Bay, USA. (Kotas, 2021).

There are at least 68 bioluminescent dinoflagellate species identified (Marcinko, Painter, Martin & Allen, 2013). Photo-autotrophic ones of these species can be easily found in large quantities on surface levels of seas and oceans. According to Sweeney (1986), even though photosynthetic dinoflagellates lose their photosynthetic capacity over time, they are able to survive up to 20 years, depending on the strain.

For the survival of dinoflagellates, a liquid medium is a must and can be said that optimum growth and maintenance temperature is between 20 to 22°C. Photosynthetic ones need light, preferably sunlight; however, they can be produced and maintained under cool-white fluorescent lamps (Cussatlegras & Le Gal, 2004)

Most bioluminescent dinoflagellates demonstrate circadian rhythm (biological clock) related to the bioluminescence intensity which is brighter in the nighttime than in the daytime (Valiadi & Iglesias-Rodriguez, 2013). Photoinhibition is another factor affecting the intensity of bioluminescence, which is a light-induced reduction in the capacity of plants', algae's or cyanobacterium's photosynthesis when there is an excessive amount of photon flux required for photosynthesis. The intensity tends to decrease during the day by photoinhibition. Studies showed that a majority of bioluminescent dinoflagellates displayed the highest response of photoinhibition in

blue wavelengths, which means that they are most sensitive to blue light. It reduces their delicacy to mechanical stimuli (Sullivan & Swift, 1994). When it comes to heterotrophic dinoflagellates (the ones which cannot do photosynthesis), the nutrition level, prey species and prey conditions in the water will affect the intensity of flashes. Without regularly providing the necessary nutrition, cells will start losing their bioluminescent abilities because they will not be able to produce necessary energy; even though energy utilization in hard conditions prioritized as swimming, bioluminescence and reproduction for *Protoperidinium*. It means that dinoflagellates can choose to invest bioluminescence more than reproduction (Latz & Jeong, 1996).

Bioluminescence can be triggered by numerous parameters. Known stimulations that induce bioluminescence flashes are changes in pH, osmotic shock, temperature or pressure, electrical shock, mechanical agitation, fluid shear and acceleration. Particular cations Ca^{+2}, K^{+1}, NH_4^{+1} and H^{+1} can also stimulate bioluminescence chemically and partly or entirely bypass the mechanical stimulation system (Hamman & Seliger, 1972). Dinoflagellates respond to these stimulations very quickly as bright flashes of light. According to Anderson, Nosenchuck, Raynolds & Walton (1988), bioluminescence can be mechanically stimulated by these parameter's changes, not by the constant values. For example, in the case of pressure, increased levels stimulated bioluminescence. However, due to circadian rhythm, stimulation during the daytime or in the light cycle produces little bioluminescence or no bioluminescence if they are in a constant lighted condition, while the cells produce bright flashes during the night time or in the dark period. Figure 2.2 shows the bioluminescent *Pyrocystis fusiformis* cell.

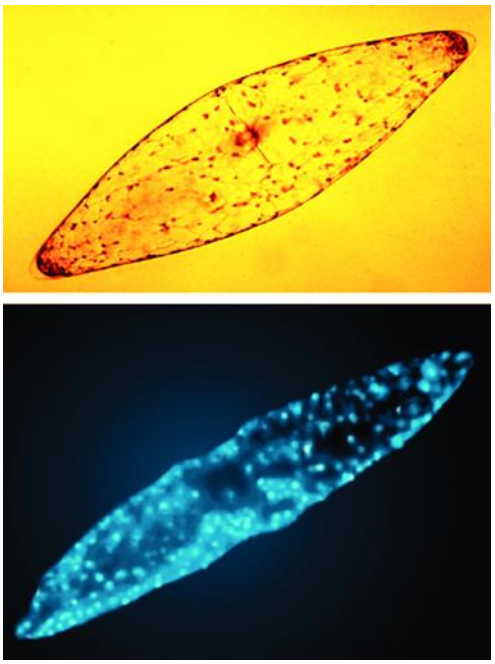


Figure 2.2. The image on top shows dinoflagellate Pyrocystis fusiformis cell and the image below shows the bioluminescence observed in the dark (Widder, 2002).

In dinoflagellates, light emission happens in two modes, which are different from each other. The first one occurs as emitting a glow; the brightness is not significant yet lasts several hours. In this mode, light is absorbed in the daytime and released at night due to the biological clock. The other one is flashing, which can be seen with a naked eye, it is bright and lasts less than a second after stimuli (Hastings, 2014). According to Deane and Stokes (2005), these flashes can last about 50 ms to 150 ms typically. However, some of the dinoflagellate species have the ability to produce a more sustained glow. In addition to that, the authors argued that flashes could vary, because dinoflagellate species have different characteristic behaviors. For example, *Lingulodinium polyedrum* (formerly known as *Gonyaulax polyedra*) flashes two or three times during the dark phase. In contrast, *Pyrocystis fusiformis* can flash many times and continue to flash if sufficiently and frequently stimulated. According to Arneson, Benyamin, Jones & Schmidt (1988), flashes of *Pyrocystis fusiformis* cells varied between 412 nm and 553 nm in wavelength but peaked around 470 nm, in the

1000 msec and 9000 msec time period. Stimulation strength also has effects on the flash intensity of dinoflagellates. Figure 2.3 shows differences in the flash intensity among species of *Noctiluca, Lingulodinium* and *Pyrocystis.*

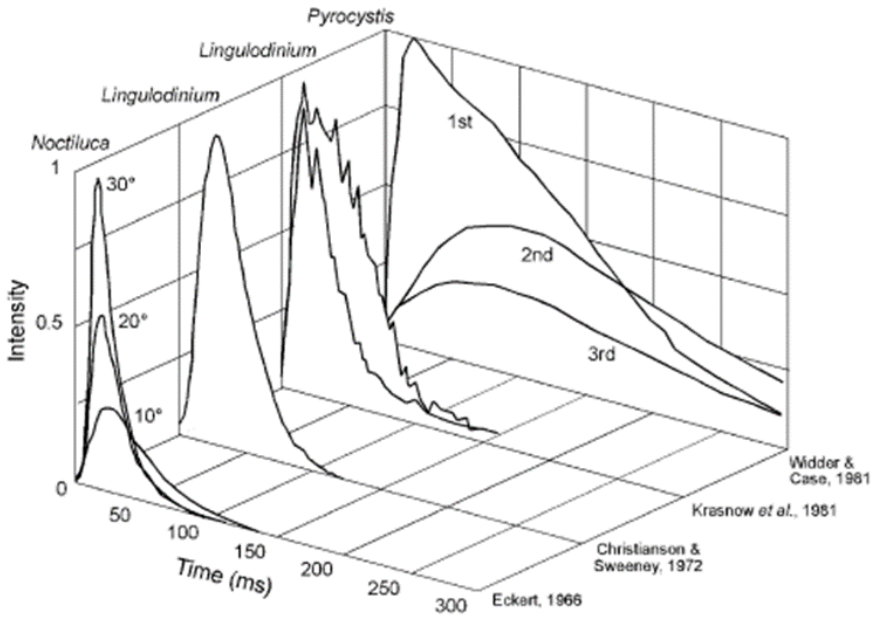


Figure 2.3. The intensity of light emission and time function for selected three bioluminescent dinoflagellates that respond to mechanical and electrical stimuli (Deane & Stokes, 2005).

As shown in Figure 2.3, *Noctiluca* shows sensitivity to temperature, which affects the plots of flash structures. For *Pyrocystis*, it can be said that variations occur in the flash structure after rapid triggers, but elapsed time is the longest. Curves belong to *Lingulodinium* display differences in emission measurements.

2.1.2 Measurement of Dinoflagellate Bioluminescence

A variety of equipment and methods have been built up to measure dinoflagellate bioluminescence when they are mechanically stimulated in situ. One method is measuring total stimulated light, which includes stimulating the organisms until their

exhaustion and recording the total amount of emitted photons during the period. The other approach is using bathyphotometers, which are used to measure the amount of light produced by dinoflagellates in a particular amount of water (Marcinko et al., 2013). Generally, a light sensor (photodiode or photomultiplier tube) is used during the process in a light-tight chamber (Latz & Rohr, 2005). However, it is argued that since there is a lack of standardized method of measurement, units and excitation, making inter-comparison between measurements in different studies becomes problematic (Bivens, Geiger, Bird & Lapota, 2001).

Recently, an analytical method called luminometry has become popular for measuring both chemiluminescence and bioluminescence due to some advantages such as sensitivity, wide dynamic range and inexpensive equipment. The measurements are done by luminometers, which are simple instruments for measuring light output of a sample for a set period of time. Photon-counting types of these instruments give the results as "photons per second". A series of conversions were performed by Veron (2013) in order to be able to interpret and compare the measurements, which are problematic due to the lack of standardization. Measurement of dinoflagellate bioluminescence was collected in photons per cell per second and converted to the lumen, which enabled comparisons with the lighting appliances used in architectural spaces. The authors used Planck's constant as a reference to calculate the photon energy. Later, they multiplied the amount of photons per cell with the total amount of cells in one mL sample to calculate total amount of energy. Since 1 candela (cd) is 1/683 Watt per steradian (sr) (National Institute of Standards and Technology, 2010) and 1 lumen is 1 cd*sr, the authors calculated the luminous flux values of the samples. The potential amount of light produced by the source in an hour by sample cells in one mL was calculated as 0.04, and increase in milliliters resulted in a higher lumen amount.

2.1.3 Excitation of Bioluminescence and Bioluminescent Responses

There are several experiments that studied the factors for excitation of bioluminescence in dinoflagellates and effects of bioluminescence response.

Latz, Nauen and Rohr (2004) studied flow sensitivity and bioluminescence response rate of four species, *Ceratium fusus*, *Ceratocorys horrida*, *Lingulodinium polyedrum* and *Pyrocystis fusiformis* with fully developed laminar and turbulent pipe flow. Laboratory cultures of the species were grown in seawater with f/2 additions and subjected to a 12:12 light/dark cycle. Cell concentration of 15 cells mL^{-1} was achieved in order to resolve individual flashes within the laminar flow. Results showed that *Ceratocorys horrida* has the highest response rate and *Lingulodinium polyedrum* has the lowest response rate in bioluminescence in laminar flow, and *Pyrocystis fusiformis* has the brightest flashes. According to the authors, the change in the response rate between laminar and turbulent flows was not significant and shear stress thresholds needed for stimulation of four dinoflagellates were different from each other. Besides, there is a positive correlation between shear stress higher than threshold values and the number of recorded bioluminescence flashes (Latz & Rohr, 1999).

Another set of experiments related to bioluminescence excitation was conducted using *Pyrocystis noctiluca* in Couette chamber with stationary-laminar and turbulent flows. Laboratory cultures of *Pyrocystis noctiluca* were grown in enriched f/2 media and, for the maintenance, culture chamber at 20 ± 2°C, 12:12 light/dark cycle, and cool-white fluorescent tubes for daily illumination were provided. In order to increase the visualization of the flow inside the Couette device, Kalliroscope® was used. After putting an adhesive tape inside the Couette device, the cylinder created turbulence during rotation, resulting in a higher bioluminescence response at a lower rotation rate. On the other hand, without an adhesive tape placed inside the cylinder, to reach the same amount of bioluminescence, a higher rotation rate was needed (Cussatlegras & Le Gal, 2004). The authors concluded that turbulence with accelerated flow is required for the strongest bioluminescence emissions since the

laminar, stationary homogenous shear flow was only able to excite very little bioluminescence in *Pyrocystis noctiluca*.

Couette flow experiments seem to show longer times of stimulation of cells than the ones in pipe-flow experiments, and there is a greater increase in the probability of multiple cell flashes in Couette flow. Figure 2.4 demonstrates bioluminescence with different rotation rates. A represents bioluminescence with the rotation rate of 5 Hz, B represents 9 Hz and, C represents 10,8 Hz.

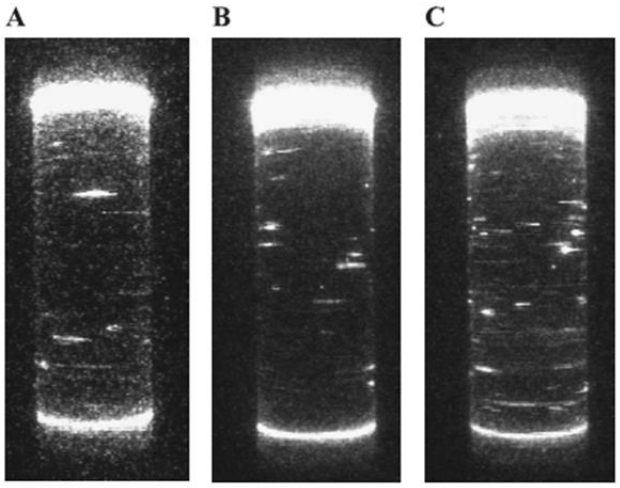


Figure 2.4. Bioluminescence with the turbulence at different rotation rates in Couette flow chamber: (A) 5 Hz, (B) 9 Hz and (C) 10.8 Hz (Cussatlegras & Le Gal, 2004).

In the bioluminescence excitation experiments done in light phase, it was observed that in *Gonyaulax polyedra* and *Pyrocystis noctiluca*, light emission levels decreased almost 2 orders of magnitude from dark-phase values because of the circadian rhythm of bioluminescence. When it comes to the bioluminescence responses of dinoflagellates to shear stress, it was seen that responses changed due to interspecific differences. *Pyrocystis noctiluca* showed a lower excitation threshold than *Gonyaulax polyedra* (Latz, Case & Gran, 1994).

2.1.4 Bacterial Bioluminescence

Calm milky seas are known for a unique type of bioluminescence. In these seas, the dinoflagellates are not much abundant. Lapota, Galt, Losee, Huddell, Orzech and Nealson, (1988) collected samples from the milky sea and discovered luminous types of dinoflagellates, zooplankton and bacteria. According to the authors, in Indian Ocean and Arabian sea, which are famous for milky seas, stimulated bioluminescence was dominated by dinoflagellates. However, the bioluminescence on the surface, displayed differences in intensity and the character, which is caused by the luminous bacteria *Vibrio harveyi.* Dinoflagellate species produced bright flashes in short durations, while luminescent bacteria produced a continuous glow. For this reason, bioluminescent bacteria in these seas were discovered as the reason for the milky image of the surface in calm waters. These bacteria are known to emit light for hours (Nealson & Hastings, 2006), and they do not require mechanical stimulation. They can continue glowing for many days even though emitted glow may be relatively faint (Miller, Haddock, Elvidge & Lee, 2006) and more than 30 species of bacteria have been discovered as bioluminescent (Dunlap, 2014). Figure 2.5 shows the satellite image of the milky sea from space.

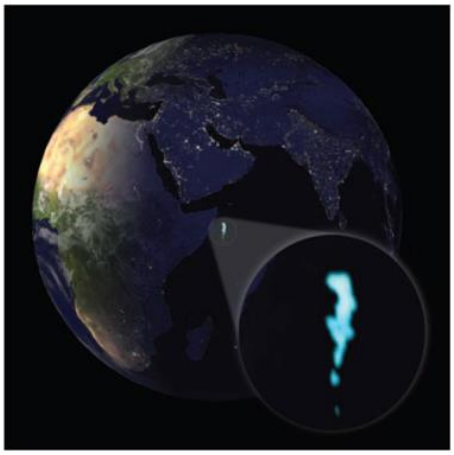


Figure 2.5. Multi-satellite composite, which provides a space perspective image of the milky sea event in the Indian Ocean on 25 January 1995.The circular inset highlights the simulated luminous bacteria with cyan false-color enhancement (Miller et al., 2006).

Being among the organisms capable of bioluminescence, bacteria have been found to live in both salty and fresh water, warm and cold environments. They can be living freely or in symbiotic relationships with a host animal (Dunlap, 2014). For example, the bioluminescent bacterium *Vibrio fischeri* is known to have a symbiotic relationship with Hawaiian bobtail squid and is mostly associated with the squid's light organ (Nyholm & McFall-Ngai, 2021).

Currently, luminescent bacteria are classified under the three families of *Gammaproteobacteria: Vibrionaceae (Aliivibrio, Photobacterium, Vibrio), Enterobacteriaceae (Photorhabdus),* and *Shewanellaceae (Shewanella*). All the strains from a bacterial species are not bioluminescent, bioluminescence is seemed to be distributed also among the phylogenetically far groups. Some of *Vibrionaceae* species are not luminous and only a few species in *Enterobacteriaceae* and *Shewanellaceae* are listed as bioluminescent. Among the bioluminescent bacteria, *Aliivibrio, Vibrio* and *Photobacterium* are genera that are commonly accepted and mostly studied (Dunlap, 2014).

According to Burtseva, Kublanovskaya, Baulina, Fedorenko, Lobakova and Chekanov (2020), under the 15 ºC temperatures in the Polar regions, *Photobacterium phosphoreum* are predominant, and in the warmer temperatures *Vibrio harveyi*, *Aliivibrio fischeri* and *Photobacterium leiognathi* are more abundant. The authors also cultured the species of luminous bacteria collected from different organs of White Sea finfishes for 3-5 days at 14 ºC medium and recorded the luminescence spectra with a microplate reader. The emission was measured spectral range of 400-600 nm. Three types of bioluminescence and two types of color (Figure 2.6) were observed. *Vibrio splendidus, Shewanella baltica* and *Photobacterium phosphoreum* had emissions peaked at 478-492 nm with blue-green luminescence and *Photobacterium* had maximum emissions in 468-474 nm with blue light of bacterial bioluminescence. Since the evolution of bioluminescence mostly occurred in the open oceans, light emission spectra are blue and centered on the wavelength of max around 475 nm, which can travel farthest in the deep seawater. The color green

follows the blue as the next common spectra, while violet, yellow, orange and red colors are rare (Widder, 2010).

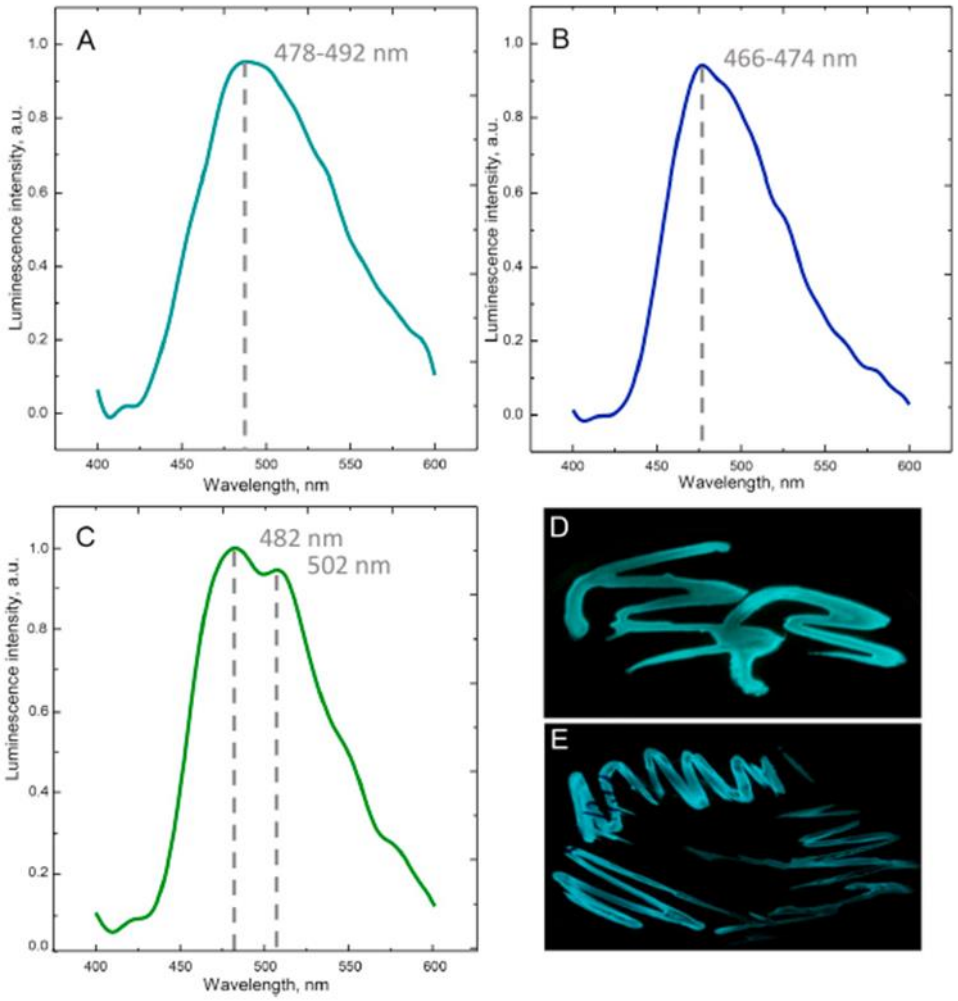


Figure 2.6. Spectra of bioluminescent bacteria with luminescence intensity in arbitrary units: (A) Aliivibrio logei, (B) Photobacterium phosphoreum, (C) Kosakonia cowanii and the colors of bioluminescence with blue-green (D) and blue (E) (Burtseva et al., 2020)

2.1.5 Bioluminescence System of Bioluminescent Bacteria

The bioluminescence system of bacteria is different from dinoflagellates in terms of autoinduction. Some behaviors of bacteria are performed only when there is sufficient amount of cells in the population. This minimum behavioral unit is called quorum of bacteria; quorum sensing (Fuqua, Winans & Greenberg, 1994), and bioluminescence is one of these behaviors. In *Vibrio harveyi* and *Vibrio fischeri* species, this feature was studied intensively (Dunlap, 2014). Barak and Ulitzur (1981) studied the autoinduction system of the bioluminescent bacterium Vibrio harveyi and discovered that when the total number of cells per cm^2 reached 10^4 (100 colonies with 100 cells or one colony with 10^4 cells), the induction occurs. And according to Martini, Michotey, Casalot, Bonin, Guasco, Garel and Tamburini (2016), the more active bacteria mean higher bioluminescence.

The presence of oxygen, high amount of autoinducer (a chemical which is detected and produced by the bioluminescent bacteria, allowing cell-to-cell communication called quorum sensing and initiating the light production after exceeding a threshold concentration) are important for bacterial bioluminescence (Miller et al., 2006). Especially oxygen has a key role in the bioluminescence of bacteria as it is directly or indirectly related with the biological process of bioluminescence (Bourgois, Sluse, Baguet & Mallefet, 2001). In some bioluminescent bacterial species, the luminescent system is found to be decreased at low oxygen concentrations (Nealson & Hastings, 1977).

The lux operon is a common gene sequence around luminous bacteria. Since the lux genes are responsible for both luciferase and an aldehyde substrate production, light emission can occur in non-bioluminescent bacteria if the cloned genes are transferred into their genomes. With the engineered bacteria, negative effects on light emission from the environment can be decreased (Bolelli, Ferri & Girotti, 2016). For example, *Escherichia coli* can be easily cultivated and can be introduced with lux operon. Observations showed that plasmid insertion containing lux operon to *Escherichia coli* is functional and effective. It can be an alternative with higher light emissions

and without the limitations of bioluminescent marine bacteria such as complex seawater medium and less tolerance to high or low temperatures (Brodl, Niederhauser & Macheroux, 2018). In another study, Gregor, Gwosch, Sahl and Hell (2018) enhanced the brightness of bacterial bioluminescence seven times more with an engineered operon. With gene engineering, highly bioluminescent derivatives of the bacteria *Bacillus subtilis* was generated (Jacobs, Hill & Stewart 1991).

2.1.6 Culture Conditions, Inducing Bioluminescence and Bioluminescence Responses

There are several factors affecting the bioluminescent bacteria cultures and their bioluminescence responses.

Environmental conditions are important for the growth of bioluminescent bacteria and optimum conditions vary depending on the species. Waters and Lloyd (1985) studied favorable conditions for growth and bioluminescence of three species *Photobacterium leiognathi*, *Photobacterium phosphoreum* and *Vibrio fischeri*. They all grew in the salt range of 0.9-3% NaCl. For *Photobacterium leiognathi*, growth and bioluminescence were observed between the temperature range of 10-30 ºC with optimum pH range 5.8 and 6.5. *Photobacterium phosphoreum* was able to grow and show bioluminescence between 5-25 ºC, but not at higher temperatures. Based on the temperature, the upper limit of pH for bioluminescence changed, but no bioluminescence was observed more than 6.8 value pH. When it comes to *Vibrio fischeri,* the organism grew and was bioluminescent between 5 to 30 ºC. To see luminescence at higher temperatures, high NaCl was required. For the pH, the upper limit was detected as 6.8.

There are numerous liquid and solid media to cultivate marine bacteria. The right amount of organic compounds for carbon and energy source and salts are essential ingredients. Artificial or natural seawater is a basic component to which nutrients and agar are added. Parmar, Shukla, Saraf and Patel (2020) pointed out that they used

seawater agar, luminous agar and nutrient agar for cultivation media, but seawater agar was proved to be the most appropriate one for the bioluminescence and growth of bioluminescent bacteria collected from coastal regions of Gujarat. The authors added that isolated bacteria were not able to grow in the absence of NaCl and showed maximum luminescence at pH 7 and 3% of NaCl concentration.

To optimize the factors which influence the growth rate and light emission, salt content, incubation temperature (the temperature for the process of incubating the bacteria), pH value, oxygen concentration, osmotic pressure, nutrient composition and concentration must be evaluated (Bolelli et al., 2016). For example, continuous oxygen supply is necessary for *Vibrio fischeri* to obtain maximum amount of emission. Figure 2.7 demonstrates the images of *Vibrio fischeri* from different views. The author also mentioned lyophilizing for long-term preservation and freeze-drying method for long-term storage.

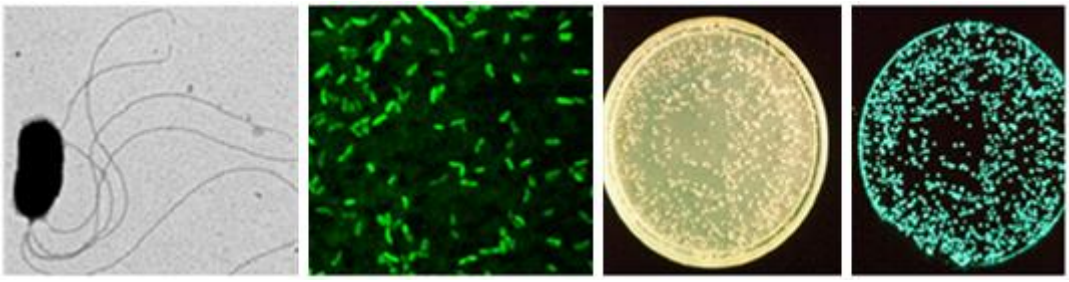


Figure 2.7. Vibrio fischeri images (left to right respectively) from electron microscope, fluorescence microscope, naked eye vision in daylight and the same plate observed in the dark (Bolelli et al., 2016).

Different stimulants can affect the bioluminescence response of bioluminescent bacteria. A recent study done by Ramesh and Meyer-Rochow (2021) presented different kinds of stimulation for the bioluminescence of organisms. Chemical stimulants for *Vibrio fischeri* were described as arginine, addition of luminescent bacterial colonies and zinc, for *Vibrio harveyi* Cyclic AMP (400 lg/ml), Tetradecanal or myristic acid while phosphate (0.03–0.05 g/ml) was found to be effective for

almost all bioluminescent bacteria including *Photobacterium leiognathi* and *Photobacterium phosphoreum*. Mechanical stimulants such as agitation, air bubbling, shaking or stirring were demonstrated to make some *Vibrio* and *Photobacterium* species glow. When luminous bacteria were exposed to UV emitting light source, they showed intense luminescence. Temperature change was defined as another important stimulant for bioluminescence. *Vibrio fischeri* Y-1 strain changed color (yellow at 18 ºC and blue at 18 ºC) based on temperature.

In another study, cultures of *Vibrio fischeri* grew on either Tryptone soya broth, Difco nutrient broth or Oxoid nutrient broth containing nutrient medium in the presence of oxygen with temperature between 20 to 26 ºC showed the highest bioluminescence. Phosphate and calcium carbonate provided cultures demonstrated stability in terms of pH and longer-lasting bioluminescence. However, in contrast to the findings of Waters and Lloyd (1985), for the upper limit for bioluminescence of pH 6.8, the optimum pH level for continuous growth was 7.8. These conditions were described for a continuous cultivation and intense stable bioluminescence of *Vibrio fischeri* cultures up to 8 weeks (Scheerer, Gomez & Lloyd 2006). Figure 2.8 shows the effect of turbidity, temperature and oxygen levels on the luminosity. As it is seen, sudden increase in turbidity decreases the luminosity level. Around 25-32 ºC, luminosity level is the highest, whereas after 32 ºC, the level starts to decrease. Furthermore, the luminosity level is highly dependent to the oxygen level in the environment.

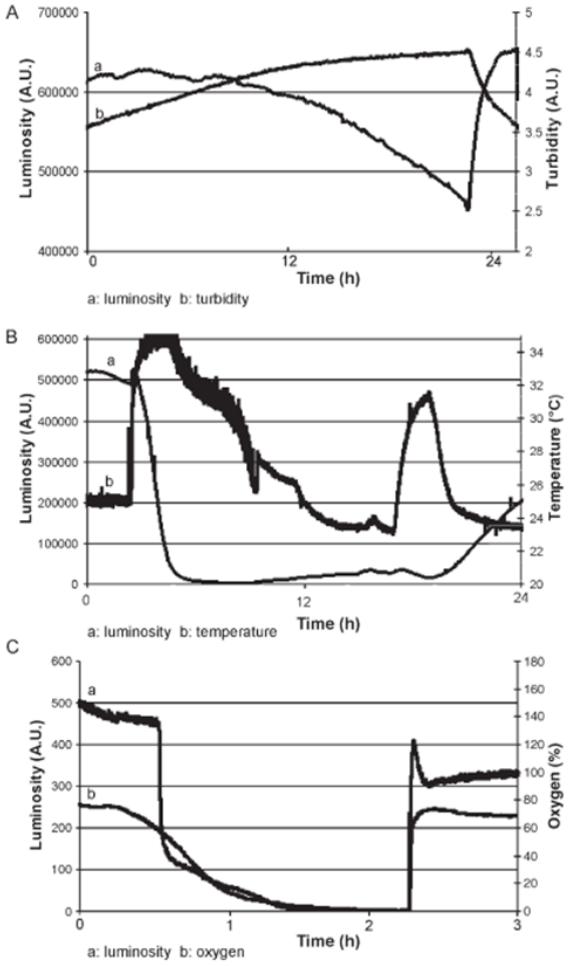


Figure 2.8. The change in bioluminescence level of Vibrio fischeri in time depending on the turbidity (A), temperature (B) and oxygen (C) levels (Scheerer et al., 2006).

There are differences in the intensity and the character of light emission among the species. Phiefer, Palmer and White (1999) studied emitted photons from the cells of two different strains of bioluminescent bacteria; *Vibrio fischeri* and *Vibrio harveyi*. They observed that only a minority of cells of *Vibrio harveyi* emitted a high amount of photons and many cells produced no light. On the other hand, light produced by *Vibrio fischeri* was rather uniform and consistent, and most cells were producing light. For this reason, batch culture of *Vibrio fischeri* was visibly more luminescent than the batch culture of *Vibrio harveyi*, even though higher photon counts than the

highest count determined from any *Vibrio fischeri* cells were measured in some of the *Vibrio harveyi* cells. The luminescence intensity for *Vibrio fischeri* in complex media was measured around $4x10^{12}$ quanta per second per ml in vivo (inside the living organism) and in vitro (cells in culture, outside of a living organism), $4x10^{7}$ in minimal media in vivo and $5x10^{8}$ in vitro. (Nealson, Platt & Hastings, 1970). It was reported that *Vibrio fischeri* reaches lower maximum light intensities than *Vibrio harveyi* strains while *Photobacterium phosphoreum* showed the brightest light intensity. (Meighen, 1999).

2.2 Algae and Current Applications

Algae is one of the oldest living creatures in the world. Prokaryotic algae were the first colonizers on the planet, and through photosynthesis, they produced oxygen by using carbon dioxide, which allowed other life forms to live. Despite their remarkable role, algae taxonomy is still being discussed by biologists due to their diversity, unexplored areas, and an insufficient amount of research. They are divided into several major groups. Based on their pigmentation, they are named green, red and brown algae. In terms of size, they are defined as microalgae and macroalgae (Chu, 2012). Microalgae are mostly photosynthetic, and they are the leading producers of the marine environment, covering 71% of the Earth (Bast, 2012).

Algae has a wide range of applications. Because of their nutritional value, they are used in the food industry and as animal feed. They play an important role in aquaculture, wastewater treatment, and even cosmetics. Moreover, due to their chemical composition, they are sources of precious components that significantly contribute to the health and pharmaceutical industries (Spolaore, Joannis-cassan, Duran, Isambert, Génie & Paris, 2006).

As a result of growing energy demand, algae has been cultivated for years in increasing amounts. Algal biomass is used for electricity generation, as well as for bio-fuel and bio-gas production (Elrayies, 2018). Algae photobioreactors are taking

attention from architecture as a facade system, as recent research demonstrated that they could be effective in terms of energy production and insulation. Figure 2.9 shows the BIQ Building in Hamburg, Germany, the first algae-powered building in the world.

Figure 2.9. The world's first algae-powered building, BIQ Building in Hamburg, Germany. (Elrayies, 2018).

2.3 Bioluminescent Bacteria and Current Usage

Bioluminescence research has gained speed in the 21st century. A good deal of articles have been published related to newly-created or improved bioluminescence-based instruments in numerous fields such as science, pharma, and medicine (Lukyanov, 2019). From one of the bioluminescent species, *Photobacterium* is used in the food industry as biosensors, in environmental monitoring, detection of the place of drown victims in criminology, as a producer of crucial chemicals as lipases, esterase, fatty acids and antibacterial compounds (Moi, Roslan, Leow, Ali, Rahman, Rahimpour & Sabri, 2017). Genetically modified bioluminescent bacteria were proposed as an alternative for environmental pollution monitoring as they produce light which is proportional to the toxic content such as organic pollutants, heavy metals, pesticides, and antibiotics (King, DiGrazia, Applegate, Burlage, Sanseverino, Dunbar, Larimer & Sayler, 1990).

2.4 Bioluminescent Algae, Bioluminescent Bacteria and Architectural Usage

Using bioluminescent algae and bacteria is a relatively new topic for architecture. However, there are several studies in the urban context and architectural contexts related to the utilization of bioluminescent lighting.

Cebi Dursun and Kozikoğlu (2015) proposed collecting waste carbon dioxide and water from the ventilation systems of existing buildings on campus to feed the bioluminescent algae farms established on the campus. The established system has pervasive algae farms and is presented as an autonomous spatial system. The proposal suggests that bioluminescent algae can be used as a light source at night and urban furniture in the campus; while increasing the campus's social interaction spaces.

By rethinking the architectural environment as a symbiotic habitat, design prototypes were developed with students containing algae. This habitat is provided an artificial day and night zone, and it uses a bioluminescent organism, *Pyrocystis lunula* to accompany the visitors in the darkness, creating an atmosphere of water reflections. Artificial vessels, which include a combination of panels and clear cushion frameworks with a mixture of water and nutrients were used for a mechanical system and motion sensors were used to be able to trace the movement of the visitors. Based on the movement of visitors, respective areas glow (Sommer, Moncayo, Sommer-Nawara & Pont, 2015). These set-ups enabled an interactive habitat within an architectural environment, pointing out the importance of focusing on interfaces between people and other organisms, such as algae.

Generated light by the algae can be used in public spaces as well as residential spaces and provides benefits of urban landscaping, decreasing light pollution and reducing contamination (Veron, 2013). In the study, the amount of light from six bioluminescent algae species was calculated and equivalent luminous flux values

were given. Table 2.1 shows milliliter ratios of samples and equivalent luminous flux values with the lumen amount of conventional light sources.

Table 2.1 Milliliter ratios of bioluminescent algae samples and equivalent lumen values (Veron, 2013).

Nomenclature	3 mL	100 mL	250 mL	500 mL	1 L	5 L	10 L
Species / unit	lm	lm	lm	lm	lm	lm	lm
Ceratium	0.04	1.36	3.39	6.78	13.55	67.75	135.51
Ceratocorys	0.12	3.99	9.99	19.97	39.95	199.74	399.49
Gymnodinium	0.00	0.00	0.01	0.01	0.03	0.13	0.25
Lingulodinium	51.34	1711.40	4278.49	8556.99	17113.98	85569.90	171139.79
Pyrocystis	40.24	1341.17	3352.93	6705.86	13411.73	67058.64	134117.28
Pyrodinuim	4.37	145.82	364.54	729.08	1458.16	7290.81	14581.62
Mean lumen amount	**16**	**534**	**1335**	**2670**	**5340**	**26698**	**53395.66**
As much light as	Bike lamp (18 lm)	Clear incandescent 40 Watt lamp (430 lm)	Incandescent 100 Watt lamp (1380 lm)	Fluorescent 36 W lamp (3000 lm)		Mercury vapor lamp (22000 lm)	High pressure sodium lamp (47000 lm)

The author (Veron, 2013) also pointed out that since emitted light by algae is diffuse, it is less efficient at heights more than 3 meters above floor level. Because of that reason, the author suggested using the bioluminescence of microalgae as orientation luminaries and local guiding lights. They can be employed in facades, entrances, galleries, illumination of ground roads, streets, parks and emergency exits. However, according to the authors, the immense potential of bioluminescence implication in architecture would be artistic one: decoration, land art, illumination of peers and marinas, and art installations.

To claim that bioluminescent light is a promising source of design in architecture, Takeuchi (2012), proposed using bioluminescent light from *Vibrio fischeri* as a curiosity builder for alleyways with negative reputation to bring them back to urban life. It can be used as a lighter for walkways which can be agitated by the movements of pedestrians in cities, and as natural environment enhancer to increase our visual

and sensorial experience with nature. The research presented a comparison between bioluminescent light and other lighting devices in terms of differences in color temperature, efficiency, lifespan, and power source. Table 2.2 shows the comparison between bioluminescent light and different light sources in view of different characteristics of a light source.

Table 2.2 Comparison between bioluminescent light and different light sources (based on information from Takeuchi, 2012).

		Color temperature	Efficiency	Lifespan (hours)	Power source
LIGHT SOURCES	**Incandescent lamp**	Warm	7-14 lm/w	1000	Electrical
	Fluorescent lamp	Warm white Daylight white Neutral white	30-100 lm/w	5000-10000	Electrical
	Mercury vapor lamp	Neutral white Cool white	35-65 lm/w	24000	Electrical
	High- pressure vapor lamp	Yellow	~100 lm/w	12000	Electrical
	Tungsten halogen lamps	Warm	30-70 lm/w	2000	Electrical
	LED lamps	RGB Warm white conversion	30-100 lm/w	100.000	Electrical
	Bioluminescent light	Cold	n/a	Infinite	Biological

Takeuchi (2012) also shared a critical observation related to *Pyrocystis*; during midnight, almost no stimulation was required for the bioluminescence of algae, and a peak was observed in the brilliance between 1 am to 3 am. From this point, it can be said that depending on the hours of circadian rhythm, bioluminescent light can be gathered from *Pyrocystis* without additional stimuli and additional energy for creating the stimuli.

Aside from using photobioreactors in building façade for biodiesel production, bioluminescent algae cultivation can be integrated into building interiors for light production. In a conceptual study by Sünger (2019), natural light is collected via

heliostats and distributed through vertical light pipes to reach the photobioreactors at the last phase. By doing so, natural light is supplied for algae to make photosynthesis; also natural light is provided in the daytime for lighting, and bioluminescent light is collected. The collected light is distributed to interiors via horizontal pipes at night.

2.5 Interior Lighting

Light is necessary for the visual perception of a human eye. For this reason, it is also an essential factor in building interiors. There have been many years of development of lighting sources and their use in building interiors, and the process is still continuing.

One of the first marks in history which started interior lighting is the production of the first practical incandescent source of lamp. In 1881, Sir Joseph W. Swan and Thomas Edison almost simultaneously developed electric light bulb. In this age of light, lamps had a pragmatic point which was simply illuminating the darkness in building interiors. In 1939 and 1940, fluorescent lamp was introduced. The fluorescent lamp produced more light at a lower cost compared to incandescent lamp, and this introduction was revolutionary at that time (Nuckolls, 1976). After almost two decades, LED lighting (Light Emitting Diode) technology was launched. With the development in time, LEDs became very popular due to the advances in their technology such as green, red and blue LEDs, reduced energy consumption, and longer lifespan (Nardelli, Deuschle, Azevedo, Pessoa & Ghisi 2017).

In the mid-sixties, the lighting approach in architecture began to change. There are new trends in the application of lighting design. Designers are demanding inventive solutions for lighting problems, not only solutions related to light quantity. New sources are getting attention, and new professionals approach the lighting from consumption point of view rather than their technical production. As engineering advances, the flexibility of lighting materials is increasing, allowing aesthetic

demands to fulfill comfortably (Nuckolls, 1976). In addition to that, since the energy demands are increasing and there are global warming and pollution problems, having more sustainable and eco-friendly solutions in the design process of the lighting has become critical.

2.5.1 Color and Light

Color originates from light and it contains wavelengths that is reflected by the surfaces, which creates the light.

There is a band of the visible spectrum for the eye in the entire electromagnetic spectrum between the ultraviolet and infrared sections. This visible energy lies between 360 nm and 760 nm on the spectrum, each representing a single color. For example, 450 nm represents blue light, 540 nm green, 600 nm orange, and 650 nm represents red. If a light source emits radiant energy, which contains several wavelengths from the visible spectrum in balance, it will appear as white (Nuckolls, 1976). The visible light spectrum is shown in Figure 2.10.

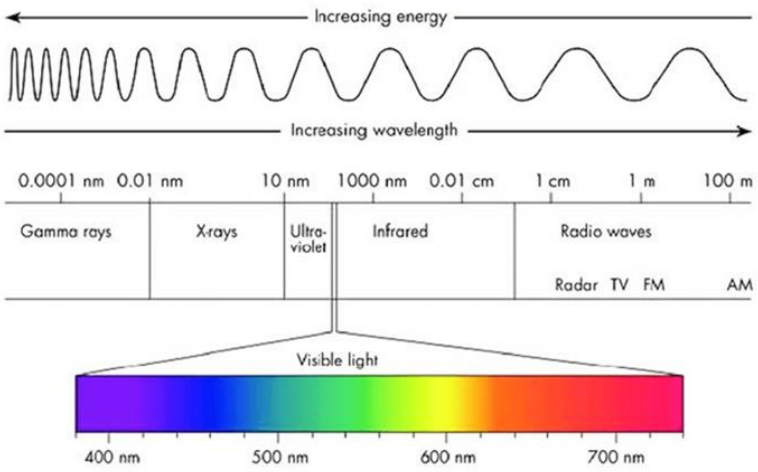


Figure 2.10. Diagram showing the electromagnetic spectrum of light with different wavelengths (Nayak,Parui, Sharma & Ratha, 2020).

In 1660, Sir Isaac Newton set up an experiment using a prism, sunlight passing through a prism created a rainbow on a surface where it landed. This experiment showed that the white light contains all the different colors in the rainbow (Achenbach, 2001). He also observed that the colors refracted through a prism do not change into other colors. When he put a board with a small hole in it and a second prism to the first setup, he deduced that there is certain number of spectral colors that do not transform to other colors, that are fundamental (Eckstut & Eckstut, 2013).

Mixing all the colors of the rainbow and creating white was Newton's conclusion. However, if red, orange, yellow, green, blue, and violet is mixed in a color palette of paint, you get anything but white, because Newton was dealing with the light and the mixture of light is different than the mixture of paints which is called additive color. Additive colors are red, green and blue (RGB) and this system is additive color system. The other system is called subtractive color system, which includes pigments to produce the color using reflected light. The subtractive colors are cyan, magenta, yellow and black which is known as CMYK. Black is referred as K or the key color (Eckstut & Eckstut, 2013). Figure 2.11 demonstrates the RGB and CMYK systems.

Figure 2.11. Additive system of colors and subtractive system of colors (Eckstut & Eckstut, 2013).

A colored light source appears when there is an energy imbalance of visible radiant energy reaches the eye from the source. Radiating more energy in some wavelengths than others creates colored light sources. In order to create systems for color-light

notations, specialists have worked and a few attempts has been established. One of the attempts is based on the black-body radiation. Black-body radiation is a fact that as the temperature of a material increases, the color of its glow also changes (Nuckolls, 1976). The physical temperature of light is expressed in Kelvin (ºK). As the iron bar heated, the color changes from black to invisible infrared, then red, orange, yellow around 3000 ºK, blue and white when it reaches its highest temperature. Below 3300 ºK, light is perceived as warm, between 3300 ºK to 5300 ºK intermediate, and above 5300 ºK cold (Miller, 1997). Another attempt is the chromaticity diagram, developed in 1931 by the International Commission of Illumination (C.I.E). This system is the dominant one and internationally accepted (Eckstut & Eckstut, 2013). Every color stimulus can be designed by a unique combination of three theoretical primaries (red, green and blue) in the system. In each wavelength, a color's spectral values are measured and the resultant combination represents the amount of these three different primaries needed to designate the color sample. After 30 years, color rendering index (CRI) was recommended as a measure of the ability and the quality of light produced by light sources (Nuckolls, 1976). How colors appear under a specific light source is expressed by the color rendering and is determined by comparing the way they seem in daylight (Miller, 1997). The rating system based on that is color rendering index (Gordon, 2003). The comparison is expressed with Ra and is measured between 1 to 100. When the changes in the color of the light is small, the index is high; when the changes are big, the index is low. The color rendering index is valuable when associated with color temperature (Nuckolls, 1976). Comparing CRI values of two light sources are valid only when they have a similar color temperature (Gordon, 2003).

2.5.2 Light on the Surfaces

When light encounters an object on its way, a number of physical phenomena occur simultaneously. The predominant ones of these phenomena are absorption, transmission, refraction and reflection of light.

Light absorption: Absorption of light is the process of the conversion of radiant energy into other forms of energy when light passes through a matter. It is largely associated with color. The absorption is selective when the light of a certain wavelength is absorbed in preference to others. Due to selective absorption, colored substances demonstrate their colors in some portion of the spectrum. This happens in almost all traditional dyes and pigments, paints, printed fabrics, pigmented plastic and other colored materials. Colored objects can be transparent, translucent and opaque. Materials which do not contain any particles to scatter light, are called transparent (Choudhury, 2014).

Light transmission: Transmission of light occurs when light can pass through objects. Visible light can be transmitted through transparent substances and illuminate objects beyond. Some of the light is transmitted and some is scattered by the translucent objects (Ford, 2021).

Refraction of light: Refraction is the change in direction of light when it passes a medium where its speed is different. This occurs when a boundary between two materials have different refractive index. For instance, when light enters into water from air, it slows down as the water is denser than the air. It causes light to continue to travel at a different angle or direction (Choudhury, 2014).

Reflection of light: Reflection happens when light encounters a surface or a boundary that bounces the light waves away due to not absorbing the radiation. The amount of light reflected by a surface is determined by its surface reflectance. It is a ratio of surface radiance to surface irradiance, and there is no specific unit for the surface reflectance. The values are between 0 and 1 (Landsat Missions, 2018). The percentage mostly does the presentation of surface reflectance.

The reflectance properties of interior surfaces are fundamental in the lighting design. The amount and the direction of the reflected light by the surfaces affect efficiency of the light distribution and the perception of the brightness of the surface by the eye. In a building interior, wall, ceiling and floor surfaces are large area reflectors affecting the redistribution of the light in a room. White and off-white finishes are high-reflecting as they allow to use the maximum amount of the available light. As the color gets darker, it absorbs higher amounts of available light. Based on the information obtained from the manufacturers of paints, wall coverings, ceiling tiles, floor coverings, machinery and the furniture, white, off-white, grey, light tints of blue or brown has the highest reflectance with 75–90%, medium green, yellow, brown, or gray 30–60%, dark grey, medium blue 10–20% and dark blue, brown, dark green, and many wood finishes has 5–10% of surface reflectance (Gordon, 2003).

2.5.3 The Measurement of Light

The science which measures the light is called photometry. There are different units and terms which are commonly used for quantification and measurement of the light.

Lumens (lm): Lumen is a measure of the total light output of a source (Nuckolls, 1976). It refers to the luminous flux of a light source in the SI unit system (Kayalı, 2021).

Candelas (cd): Candela is the unit of measurement for the luminous intensity in a particular direction by a light source. To illustrate the light patterns, distribution curve or polar diagrams are commonly used (Gordon, 2003). Figure 2.12 shows a polar graph of a fluorescent luminaire.

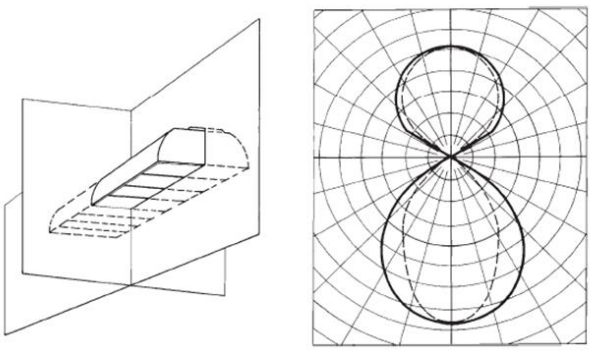


Figure 2.12. A fluorescent luminaire's polar graph (Gordon, 2003).

Lux (lx): Lux is the measurement of the density of light on a surface. Illuminance is measured in lux in the metric system or in footcandles in the imperial standard measuring system. The amount of illumination that a surface receives depends on the distance from the light source and the intensity of the light source (Judge, 2017). Figure 2.13 demonstrates the foot-candle and lux, 1 foot-candle is 1 lumen per ft^2 and 1 lux is 1 lumen per m^2. It should be noticed that the light source is in a distance of 1 foot for the footcandles and 1 meter for the lux.

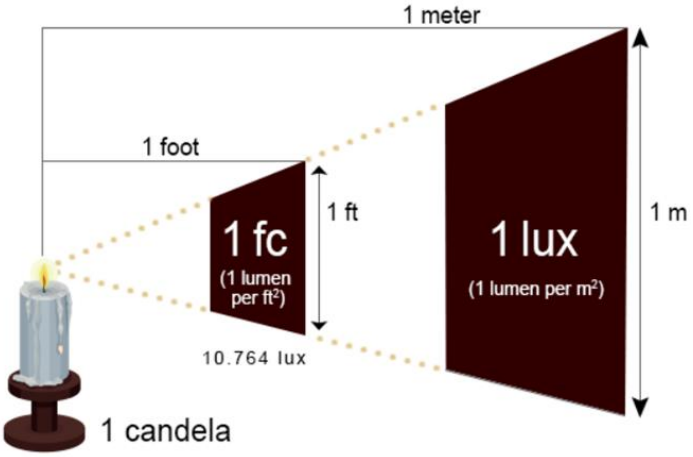


Figure 2.13. The difference between footcandles and lux (Szewczyk, 2018).

Illumination depends on the distance to the light source and the intensity of the light source. As you get closer to the light source, the lux value increases. If the intensity of the light source is higher, the lux value will be higher too, as the amount of light falling on the area will also be higher.

The light emitted by the source in certain direction gives the intensity of the light source. The total amount of light per unit area on a surface describes the illuminance, and the light which is reflected back towards the eye from a surface describes the luminance. Illuminance is commonly used for measuring the amount of light for architectural spaces since it is easy to measure and the equipments are inexpensive (Gordon, 2003). How illuminated an environment is generally expressed via its lux value, a higher lux value means a higher level of illumination. If the same amount of light is distributed on two different sized areas, small area will be perceived brighter and the lux value will be higher. Lower lux values will be measured and a dimmer image will be perceived in the larger area (Yılmaz, 2019). With a simple light meter or a lux meter, readings with approximate values can be done for architectural applications (Nuckolls, 1976).

Lighting design for an architectural space can be done based on the changes in the illuminance levels. Different tasks may need different amounts of light. For example, a work environment or an office needs a higher amount of light than a sleeping or a resting room. Minimum average illuminance levels recommended to be provided based on the function of architectural spaces were shown in the Table 2.3.

Table 2.3 Recommended illumination levels for spaces of different functions (based on information from The Chartered Institution of Building Services Engineers ,CIBSE, 1994)

Areas common to most buildings	**Lux**
Entrance hall, lobby, waiting room	200
Enquiry desk	500
Corridor, passageway, stairs	100
Atria	50-200
Changing room, cloakroom, lavatory	100
Rest room	150
Canteen, cafeteria, dining room	200
Kitchen	300
Offices	
General offices	500
Computer workstations	300-500
Conference room, executive office	300-500
Hotels	
Entrance halt	100
Reception on desk	300
Bar, restaurant. dining room, lounge	50-200
Bedroom	50-100
Kitchen	150-300

For lighting design and calculation of lux amounts in the architectural spaces, lighting simulations can be used. DIALux Evo is one of these programs developed by the German Institute for Applied Lighting Technology (DIAL) (Amoêda & Carneiro, 2020) in 1994. The software can calculate and visualize daylight and artificial light in exterior and interior spaces, road lighting and emergency lighting (Davoodi, Johansson & Enger 2014). The main feature of the software is that, every lighting fixture manufacturer can insert the technical properties of their products into the software (Çelebi, 2007).

The program uses a modified version of radiosity as a calculation method and includes ray tracer, which can create photorealistic visualizations (Davoodi et al., 2014). The radiosity method calculates the direct and the reflected illuminance levels created by natural and artificial light sources. The method operates according to the conservation of energy principle. Radiosity calculation determines the reflected and absorbed part of the energy coming out of the light sources. Each light-receiving

surface acts as a light source according to the amount of energy falling on it, and the whole scene is illuminated as in real life (Çelebi, 2007). In addition to that, a surface may be self-luminous. With the diffusion method, an equation is created for each surface. This equation describes the light emitted from other surfaces and if there is any, the luminance of a surface itself. The program is also able to calculate the daylight multiplier (Işık, 2009). The program allows users to choose or arrange the geographic locations with a specific day and time for more accurate calculations (Çelebi, 2007). Based on the performance data of the luminaires, the software can also evaluate energy demands and the efficiency of lighting solutions (Amoêda & Carneiro, 2020).

The software is customizable. It has 3D modeling tools which allow users to model the site and building with construction elements such as structural elements, floors, walls, roofs and apertures. Surface materials can be assigned from the software's database as well as from the data input by the user. Furthermore, importing 2D cad files and 3D cad files with a complete building from other CAD design tools is possible (Amoêda & Carneiro, 2020). Inputs are project information, the geometry of the room, calculation parameters, light source, location of the light source and layout of the light sources. Outputs can be briefly described as project information, details and diagrams for lighting devices, light distribution, illumination amounts and visualization of the room’s luminosity in 3D dimensions (Çelebi, 2007). The outputs and the calculation results can be saved as picture file formats, movies, electronic printouts or can be printed on a paper (Davoodi et al., 2014).

2.5.4 Household Light Bulbs

Light sources commonly used for general lighting in households are incandescent, halogen, fluorescent and LED light bulbs.

Incandescent Light Bulbs: The incandescent lambs basically consist of a wire which is sealed with an evacuated glass in order to keep the filament inside away

from water vapor and oxygen. With the electricity connection, the current passes through the wire, creating heat and emission of light (MacIsaac, Kanner & Anderson, 1999). These light bulbs were economically manufactured; however, the electricity used to emit light is also converted into heat which fritters away the electricity. Since incandescent lamps are not efficient in terms of energy, they have been abandoned in households. In addition to that, incandescent light bulbs have high amount of CO_2 emissions and for this reason, 40, 60, 75, and 100 watt incandescent light bulbs were banned gradually with the EU decisions against global warming (Ayan & Turkay, 2017).

Halogen Light Bulbs: Tungsten halogen lamps have tungsten filaments like incandescent light bulbs, but they are filled with halogen gas and have a quartz tube. The lifespan of the halogen lamps is longer than the incandescent light bulbs. They provide better quality of light and better color rendering due to being closer to daylight compared to their incandescent counterparts (Miller, 1997). However, the light output is smaller; therefore, it is more appropriate to use them in small housings (Nuckolls, 1976). They have a slightly blue-colored light with higher temperatures and it is accompanied by ultraviolet radiation, which is undesirable when it comes to human health (Bloom, Cleaver, Sayre, Maibach & Polansky, 1996).

Compact Fluorescent Light Bulbs (CFL): Fluorescent light bulbs are one of the electric discharge light sources containing a small amount of mercury. They have an inert gas inside, which is kept at low pressure, and when these light bulbs are lit, thin film of fluorescent material is activated and produces light (Nuckolls, 1976). Compact fluorescent light bulbs are remarkably more efficient than incandescent and halogen light bulbs. For this reason, they have been used in building interiors for years. However, the color rendering quality is less than the equivalent incandescent sources, even though manufacturers have produced warm white and cool white versions of these tubes throughout years (Miller, 1997). The other disadvantage of these light bulbs is that the mercury inside is toxic. At the end of their lifespan, they should be adequately recycled (Ayan & Turkay, 2017).

Light Emitting Diode Light Bulbs (LEDs): Light Emitting Diode light bulbs are solid-state light sources. The light occurs inside this solid-state material which includes two different sorts of semiconductor material. These materials are called p and n materials. Basically, atoms of p and n move towards the semiconductor sandwich junction, creating an energy level difference that results in light radiation (Bommel, 2019) The development of this technology allowed low energy consumption, and CFLs stayed way behind LEDs in terms of energy efficiency (Ayan & Turkay, 2017). After being commercially available, LEDs have become very popular as they are cheap, efficient and less-power consuming than conventional light sources. In addition to that, colorful LEDs, as well as white LEDs, are appropriate for different architectural installations. However, there is a lot of carbon emission in the manufacturing process of semiconductors and these materials have undesirable levels of toxicity for the environment. Therefore, researchers are developing organic LEDs (OLED) to reduce carbon emission and increase efficiency (Bhatnagar, 2018).

2.6 Case Studies

The function and usage of natural systems and living organisms have always influenced scientists, architects and designers. However, the complexity and the requirements of living systems may limit their production and use in construction. In this section projects, installations, exhibitions, and biologic light sources produced by using algae and bacteria were presented.

2.6.1 Biological Light Sources

In this section, light sources produced based on bioluminescence and the biological reaction were presented. In these light sources, bioluminescent algae or bacteria were used to gather the light.

2.6.1.1 The Bio-Light 1

A microalgae production company located in California, USA, produces dinoflagellates, specifically the *Pyrocystis fusiformis*, which is collected from the coast of San Diego. The company names their products as PyroDinos and sells them to buyers.

The company has been attempting to create a new renewable light source by using their natural products from *Pyrocystis fusiformis* since 2020. Figure 2.14 shows their prototype.

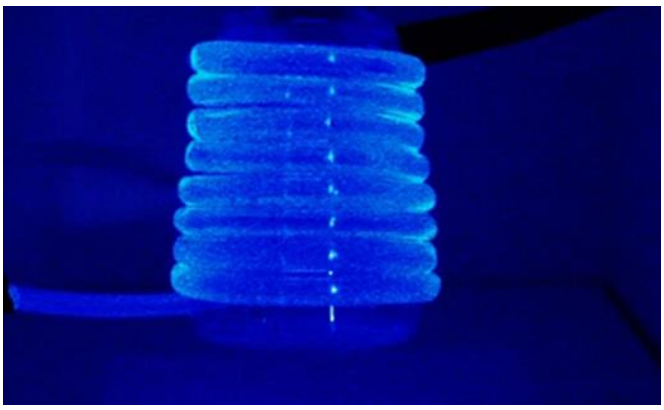


Figure 2.14. The Bio-Light 1 prototype with 12 to 15 liters of bioluminescent media developed for exhibitions and gallery presentations (Pyrofarms, 2020).

According to the experiments, the Bio-Light can work for 20 minutes with only the help of gravity with 12 to 15 liters of bioluminescent algae. The prototype is able to produce light for about an hour and a half if a small recirculation pump is used. The light can run again throughout the night with one-hour rest breaks for the algae to produce more luciferin and luciferase enzymes, which create the bioluminescence. Larger volumes can be more effective, but for now, the company is trying to make a practical system that can be transported and shipped easily.

The *Pyrocystis fusiformis* inside the Bio-Light can recharge in filtered sunlight (indirect sunlight) the next day, and as they proliferate, they can produce even more light night after night. The company is theoretically suggesting a battery-powered recirculation pump that uses a small solar panel to recharge in order to make the whole system a totally renewable light source with minimal care. (Pyrofarms, 2020).

2.6.1.2 The Bio-Light 2

Designed by Dutch designer Teresa Van Dongen, this bio-light is an elegant brass lighting fixture that uses bioluminescent bacteria as a light source. The bacteria are *Photobacterium* species, isolated from the octopus' tentacles by B.M. Joosse and R.M.P. Groen, two Life Science and Technology students at the TU Delft (Dongen, 2014). When exposed to oxygen, these micro-organisms emit soft blue light. (Stinson, 2015). Figure 2.15 shows this biological light called the Ambio Light and the blue light emitted by the bacteria.

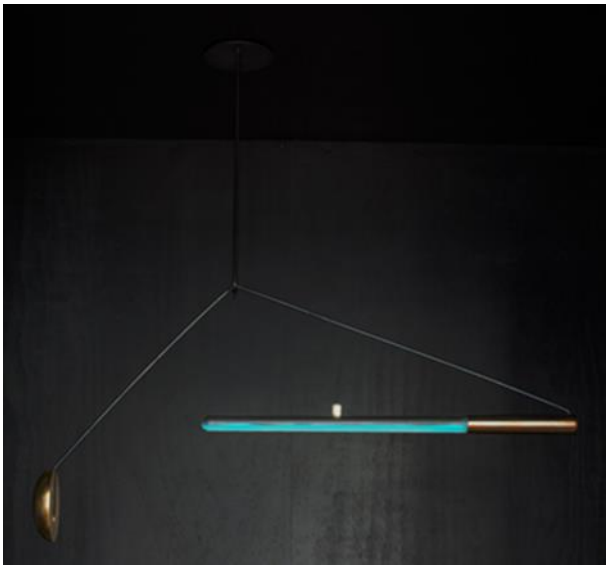


Figure 2.15. The Bio-Light 2 consisting of a glass tube filled with bioluminescent bacteria media and balanced weights for movement (Dongen, 2014).

The Bio-Light 2 consists of a glass tube filled with bioluminescent bacteria in a saltwater solution. This solution is an artificial seawater medium with the proper nutrients and food (Hobson, 2015). In order to illuminate the Bio-Light 2, balanced two weights and a glass tube half-filled with seawater was designed, and with a gentle push, the weights keep it moving and create the glow (Dongen, 2014). The swinging of the artificial seawater and the bacteria back and forth makes the lamp glow for up to 20 minutes. In the scientific setup, it is possible to sustain the bacteria for three weeks; however, the bacteria can be alive only for a few days in the tube. For this reason, Dongen and the designers are investigating how to keep them alive for longer (Hobson, 2015). The goal of the designers is to create a work in which the liquid food is constantly added to the seawater medium for the bacteria and abundant amount of this liquid is constantly drained without the use of electricity. In theory, this work can keep the population alive for an extended period of time and can make the Ambio Light self-sufficient enough to be used as a living lamp for the buildings (Caula, 2014).

2.6.1.3 The Bio-Light 3

A biotechnology company founded by Sandra Rey in 2014 in Paris, France is developing natural sources of light through bioluminescence. The company's goal is to create natural light via micro-organisms for more sustainable cityscapes. The organization is working with various fields, such as architects, construction and real estate, in order to implement bioluminescence in the cities (Stone, 2020).

The company developed a lighting solution by genetically modifying *E.coli* bacteria with DNA found in the bioluminescent Hawaiian bobtail squid (Cullmann, 2020). The scientists used genes coding for bioluminescence from bacteria that lives in symbiosis with squids. These genes were inserted to a non-toxic and non-pathogenic type of *E. coli* bacteria. Once engineered bacteria are grown, they are encapsulated into a transparent shell with a nutritive solution and all the other elements for bacteria to grow and produce light (Glowee, 2016). The resulting lamps, glow sticks and other

forms of lighting function like aquariums and require no electricity. The company showcased its technology with a “Glowzen Room” (Figure 2.16), inviting visitors to experience the dim turquoise light (Cullmann, 2020).

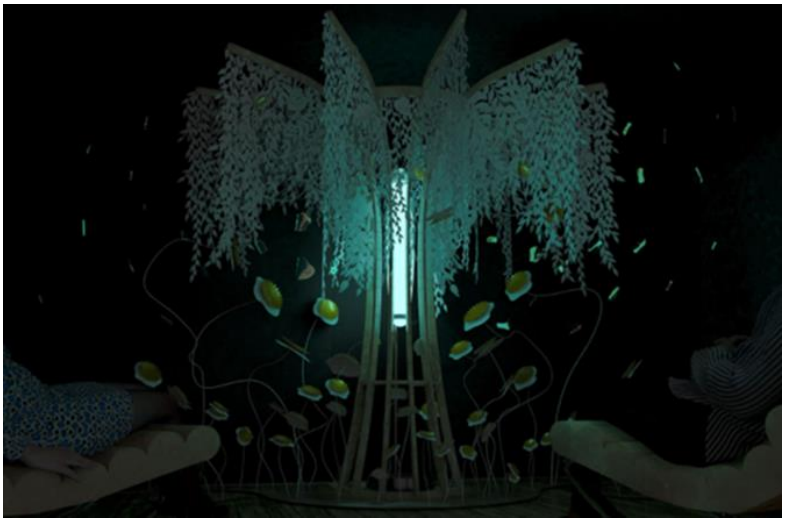


Figure 2.16. The Bio-Light 3 in the Glowzen Room located in Rambouillet, France, where visitors can experience the bioluminescent light (Zarley, 2022).

The Glowzen Room was created by following the biophilic design principles. According to the company, the room gives a relaxation experience offered by bioluminescence, improves concentration, creativity and mental health. Reduces stress by reducing systolic pressure and helps people to calm down by decreasing stress hormone production and heart rate. The experience in the room was established as 17 minutes precisely, and the sound also accompany the relaxation feeling. In addition, the organization pointed out that the blue-lagoon wavelength is already in use in chromotherapy to relax. However, the bioluminescent lighting source of Glowee consumes two times less electricity than a chromotherapy device, it is biodegradable and consumes the equivalent of 2 flushes a day (Glowee, 2018).

The company offers bioluminescence as an alternative solution which can reinvent many uses of light, even though the vision is not to entirely replace electric light with

bioluminescence but to offer a global solution that can reduce %19 of the electricity consumption for lighting purposes. In addition to helping, the bioluminescence lighting approach can be a solution for the night time lighting restrictions. Bioluminescence can be used at shop windows or in event industry, where there is a commercial added value (Figure 2.17); at monuments, building facades, as street furniture and signage where electric light can be replaced; in festivals, natural reserves, construction sites, emergent countries, where electricity cannot be brought; dark areas like tunnels (Figure 18). The transparent case designs can take almost every shape and stick to surfaces, and it allows living lights to shine from statues to buildings (O'Hare, 2016).

Figure 2.17. Bioluminescent lighting concept illustration with bioluminescent bacteria in sticker form on shop windows for French streets (Glowee, 2016).

Figure 2.18. Illustration of possible implementation of bioluminescence in a tunnel at night (Glowee, 2016).

The company develops several types of products to address the challenges for different kinds of uses of light. The products can be encapsulated into many different containers. The earlier version of the products consisted gel material, composed of bacteria and nutrients which allowed a wide range of forms to be produced. The bioluminescent raw material also can take a liquid form. With the liquid version of the material, the company developed a bioreactor (Figure 2.19) that can control the level of bacteria and the nutrition inside the system by refilling and cleaning it out. (Glowee, 2016). The bioreactors are already used with microalgae for building facades, and it may be more beneficial to use them with bioluminescent bacteria to adapt the technology to the architecture and recover the local energy.

Figure 2.19. Bioluminescent bioreactor developed by the company that can control the bacteria and necessary nutriments in the system, refill and clear it (Glowee, 2016).

The overall idea is to save limited natural resources like rare materials used in LEDs, reduce light pollution caused by traditional light systems and decrease the environmental footprint of lighting. The raw material of bioluminescence can grow indefinitely, have organic byproducts which can be neutralized or revalorized. In addition to that, bioluminescent light does not cause harm to insects, does not destroy ecosystems and wildlife and does not disturb insects, birds and trees as the traditional lighting appliances do.

2.6.1.4 The Bio-Light 4

The electronics manufacturer company in Amsterdam, Holland, created “Microbial Home” project as a domestic eco-system and a lighting fixture. It was presented at Dutch Design week in 2011. The system proposes using methane gas and other household waste to feed the bioluminescent bacteria (Figure 2.20) (Koerner, 2011).

The bacteria in the system produce a soft green light in a sustainable cycle, and the light could be powered as long as there are nutrients. Hand-blown glass cells house the bioluminescent bacteria solution and are mounted on the wall. Through silicon tubes, cells are connected to a food source. The methane gas, which is the primary food source for the bacteria, is converted from bathroom waste and vegetable trimmings with the help of a methane digester. The demonstration is located in the bio-digester kitchen island of the company, which is the central hub of the Microbial Home (Cha, 2011).

Figure 2.20. The Bio-Light in the Microbial Home project contains bioluminescent bacteria and was designed as an ambient light source (Koerner, 2011).

2.6.2 Projects, Installations and Exhibitions

The projects carried out to investigate the potentials of bioluminescent organisms and their usage, installations and exhibitions that allow visitors to interact with the bioluminescence were introduced in this section.

2.6.2.1 Genetic Barcelona Project

Founded by the Genetic Architectures Research Group & Office and the Bio Digital Architecture Master Program in the School of Architecture of UIC Barcelona, the ESARQ developed a project called Genetic Barcelona Project in 2005, where biology met genetics and digital techniques and applied to architecture. In the first phase of the project, with the use of green fluorescent protein (GFP), they worked on trees to turn them into street lights and illuminated plants for houses without any electricity (Figure 2.21). The researchers pointed out that in terms of durability, the leaves of the modified trees have the same amount of luminescence after more than ten years. Little lemon trees are able to continue growing as long as the soil conditions are available and their branches can manufacture them. However, initially, the efficiency of lighting was inferior, and to have the proper amount of lighting, unique light inputs were needed (Estévez, 2016).

Figure 2.21. The first phase of Genetic Barcelona Project, light of the lemon trees with GFP (on left), a simulation of a possible world of Casa Mila by Antoni Gaudi with GFP lemon trees (in the middle). The pictures on right above and right below demonstrate the difference between a regular lemon tree leaf and another with GFP. (Estévez, 2016).

In the second phase of the project, researchers created Bio-lamps that work as a kind of battery with bioluminescence in 2008. By using bioluminescent bacteria which origins from abyssal fish, they systematically illuminated an apartment with the bioluminescence without electricity (Figure 2.22). According to the authors, the second phase of the project was more effective than the first phase in terms of lighting; however, durability was shorter than the first phase. These bio-batteries required change in every ten days, and manufacturing the special lamps carrying the bioluminescent bacteria and guaranteeing air-tightness, oxygen and food for the bacteria was more complicated than the bioluminescent trees (Estévez & Navarro, 2017).

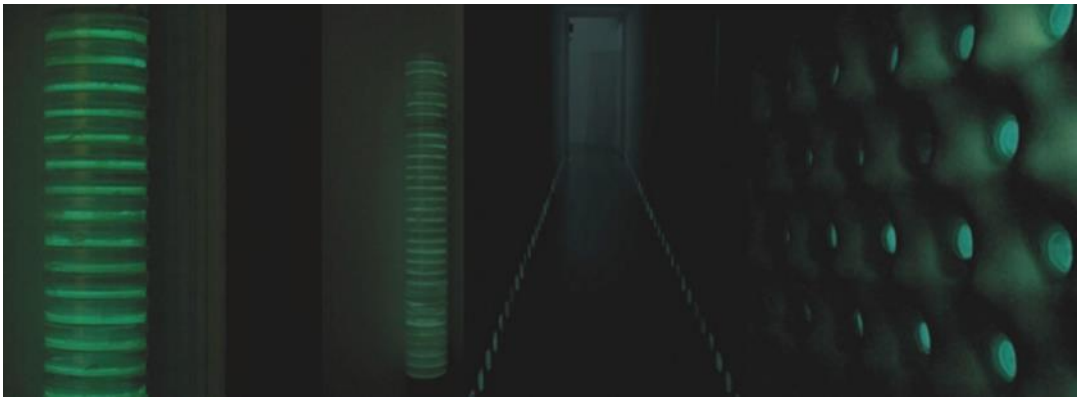


Figure 2.22. The Bio-lamps with bioluminescent bacteria and fully illuminated apartment without electricity; second phase of the Genetic Barcelona Project which was carried out between 2007 and 2010 in Barcelona, Spain (Estévez & Navarro, 2017).

2.6.2.2 Bioluminescent Field and Interference Projects

Research was conducted by German designer Nicola Burggraf to demonstrate the potentials of bioluminescence by using *Pyrocystis lunula*. To induce bioluminescence, different kinds of stimulations were used such as tilting, shaking, stirring rotating and pouring. It was explored that 200 ml of *Pyrocystis lunula* shows

0.6 lux of illuminance. Based on the research, the installation Bioluminescent Field and Interference projects were exhibited in public to see the dinoflagellates' response to motion and sound. The Bioluminescent Field project had 60 delicate glass vials carrying the algae with a saltwater medium connected to a reactive floor with thin poles (Figure 2.23). When the visitors entered the dark room where the installation was located, movement caused algae to produce flashes of blue light. It is indicated that algae acted as a biological motion sensor which activated by the visitors. In the Interference project, the response of algae to the acoustic waves was explored. A dense population of dinoflagellates in a saltwater medium was prepared which is exposed to the acoustic impulses in a choreography. According to the findings, certain frequencies immediately stimulate the algae and trigger bioluminescence as a response to the sound. The installation allowed the audience to experience sound waves rendered visible by bioluminescent organisms (Burggraf, 2012)(Burggraf, 2014).

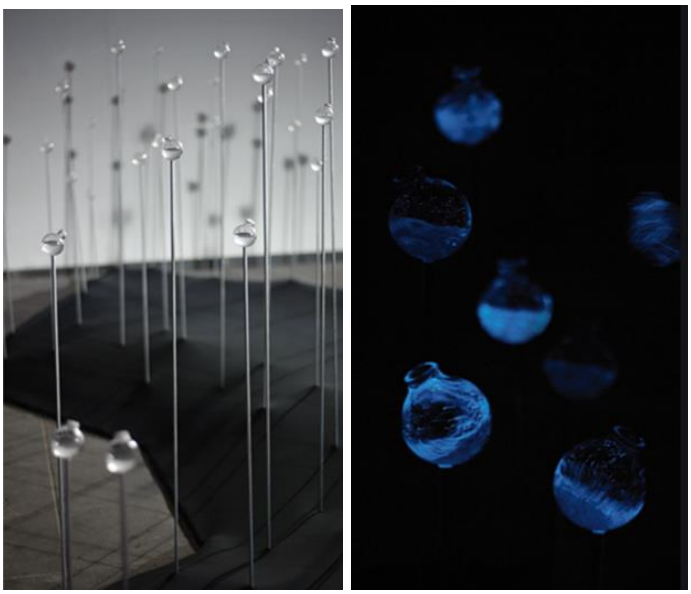


Figure 2.23. The installation of Bioluminescent Field project in Palmengarten, Frankfurt, Germany, in 2010 and the glow of bioluminescent organisms at dark when the visitors come (from left to right respectively) (Burggraf, 2012).

Figure 2.24 shows the Interference installation exhibited in Palmengarten, Frankfurt, Germany. The visitors were able to observe the bioluminescent organisms' response to the sound and vibration (Figure 2.25).

Figure 2.24. The Bioluminescent Interference Installation in Frankfurt, Germany in 2012 (Burggraf, 2012).

Figure 2.25. The bioluminescence response of algae to the sound waves in the Interference Installation in Frankfurt, Germany (Burggraf, 2012).

2.6.2.3 Glowing Nature Exhibition

A temporary exhibition called Glowing Nature was held in Afsluitdijk, the Netherlands, between November 2017 and January 2018. In the exhibition, 20 to 50 m^2 of bioluminescent algae were used in a polymer shell to demonstrate what street lights and pedestrian roads could be made from in the future. The installation allowed people to interact with the algae (Figure 2.26). Standing and touching the polymer shell surface caused algae to glow (Foth & Caldwell, 2018).

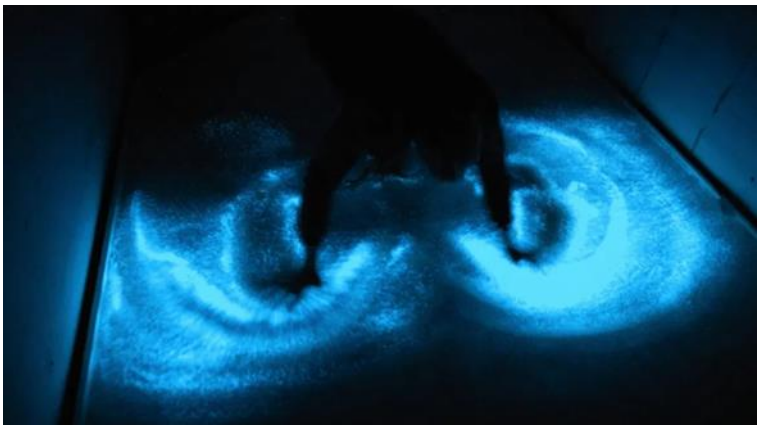


Figure 2.26. The glow of bioluminescent algae during the interaction in Glowing Nature Exhibition in Afsluitdijk, the Netherlands (Studio Roosegaarde, 2017).

The installation was exhibited in one of the historical bunkers in Afsluitdijk. To increase the awareness, bioluminescent algae were used on-site (Manen, 2020). Figure 2.27 shows the on-site installation of the historical bunker.

Figure 2.27. Glowing path to the installation of Glowing Nature in Afsluitdijk, the Netherlands (Studio Roosegaarde, 2017).

2.6.2.4 One Luminous Dot Installation

The One Luminous Dot installation is a continuation of the Bio-Light 2; the Ambio Light project which was exhibited in the Louvre museum, Paris and in the Dutch Design Week Eindhoven in 2015. The installation includes glass tubes containing bioluminescent bacteria that shape a star (Figure 2.28), and movement causes bacteria to light up (Dongen, 2015). In the installation, an electro-mechanical motion was designed to excite bioluminescence in bacteria without damaging the cells (Sabik, 2015).

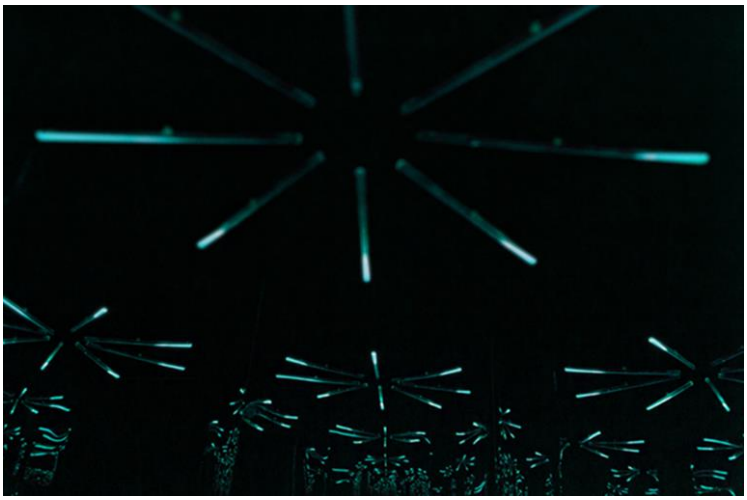


Figure 2.28. The One Luminous Dot installation with glass tubes filled with bioluminescent bacteria, exhibited in Paris, France, in 2005 (Dongen, 2015).

2.6.3 Living Bioluminescent Cultures for Commercial Purposes

For commercial purposes, cultures containing bioluminescent dinoflagellate *Pyrocystis fusiformis* or bioluminescent bacteria *Vibrio fischeri* have been produced. In this section, these cultures, reviews from the buyers and care guides to sustain the organisms were presented.

2.6.3.1 Living Bioluminescent Dinoflagellates

The Dinoflagellates have been cultured for commercial purposes. A company from North Carolina in the USA produces *Pyrocystis fusiformis* in borosilicate glasses for interested buyers (Figure 2.29). Each culture product contains 100 mL of material. Light requirement is defined as 200 to 400 foot-candles of fluorescent light with 12 hours of light/dark cycle, and optimal temperature is indicated as 22 ° C (Carolina Biological Supply Company, 2021).

Figure 2.29. Bioluminescent dinoflagellate Pyrocystis fusiformis in borosilicate glass with salt-water medium (Carolina Biological Supply Company, 2021).

According to the 37 reviews from the buyers of the product, 29 buyers were satisfied with the light amount and eight people were not satisfied with their purchase. From the four of eight people explained their dissatisfaction as having no illumination, two people explained it as having their culture dead immediately after the arrival. The other two expressed that they were expecting more illumination than they observed.

Another company in California has a commercial product including *Pyrocystis fusiformis.* They are like small aquariums in a spherical glass tube called Bio-orbs, and with a gentle swirl, produce natural light at night (Figure 2.30). The product has an optimal temperature of 17-26 ° C for the dinoflagellates. It needs indirect (not direct) sunlight and dark at night every day, and produces oxygen during the daytime like a plant. According to the company, sixty days of lifespan is a guarantee for the product (Pyrofarms, 2021).

Figure 2.30. The sphere glass aquarium product with 15cm diameter that contains bioluminescent algae (Pyrofarms, 2021).

According to the 35 reviews from the buyers of small bioluminescent sphere, 32 people were satisfied with the glow that they received from the product, and they recommended it. Three buyers were not satisfied with the product and did not recommend it. The reasons for not recommending the product were related to the shipping problems and having no glow. For the large sphere, there are 31 reviews from the buyers and 27 of them were satisfied with the glow and the product. Four people were not satisfied with the product because of observing very little glow or no glow, receiving dead culture in the arrival, and having the culture dead in a month even though the guarantee of the lifespan was at least 60 days.

2.6.3.2 Living Bioluminescent Bacteria

For mostly educational purposes, a company in North Carolina, USA, produces *Vibrio fischeri*, which are bioluminescent bacteria species. The culture is a gram-negative, rod-shaped bacteria and it is cultured on photobacterium agar at 25 °C in tubes and in plates (Figure 2.31) (Carolina Biological Supply Company, 2021).

According to the 12 reviews from the buyers of the bioluminescent bacteria product, 10 people were satisfied with the results of the light and two people explained their complaints as having dead culture at arrival and finding it difficult to sustain the culture.

Figure 2.31. Bioluminescent Vibrio Fischeri cultures. From left to right; the culture plate, the culture tube and the bacterium kit that are produced for educational purposes (Carolina Biological Supply Company, 2021).

2.6.3.3 Care Guide for Commercial Bioluminescent Algae

Care and handling are important for *Pyrocystis fusiformis*. According to the companies providing the species for commercial and educational purposes, the culture may need a week after arrival to recover before showing the bioluminescence activity. A new circadian rhythm should be established. Average room temperatures (between 18-26 °C) are ideal, and rapid temperature fluctuations must be avoided. The culture needs low to moderate light during the daytime to sustain. For this reason, a typical room with indirect sunlight is appropriate. For the places without access to sunlight or for educational/observational purposes, cool white fluorescent or white LED lamp of 200-400 foot candles with a lamp timer set up for 12-hour cycles of light and dark is convenient. Keeping them on the same photoperiod cycle is more convenient, but the cycle can be altered based on users, and in a few weeks,

the culture can adjust themselves to a new cycle. Commercial cultures should not be exposed to direct sunlight or incandescent light bulb because of the probability of excess heat that can damage the culture. At least 30 minutes after the beginning of dark cycle is when the bioluminescence is the most evident, and the bioluminescence can be observed only in the dark portion of the cycle. Depending on their circadian rhythm, after 7 pm in a darkened area, they can start showing bioluminescence. Shaking or gently swirling the container will induce bioluminescence by agitating the cells and vigorous manipulation may reduce the number of instances that bioluminescence can be observed. The glow may fade as the culture get tired of being agitated multiple times; therefore, the culture needs to recharge in the light cycle before showing bioluminescence again. As the dinoflagellates reproduce, the bioluminescent glow will intensify. Healthy cultures are recommended to divide approximately every month and feeding them with saltwater medium once every two weeks is beneficial for their longer maintenance. The cultures are sensitive to pollution and can go wild when pollutants invade their habitat. (Pyrofarms, 2021) (Carolina Biological Supply, 2016).

2.6.3.4 Care Guide for Commercial Bioluminescent Bacteria

Among the bioluminescent bacteria, *Vibrio fischeri* also needs proper care. The optimal growth temperature is 25° C, which means that they can live easily at typical room temperature. These cultures should be subcultured 2 to 3 times per week to sustain the glow. They need oxygen and photobacterium agar to live. They should be inoculated more heavily than other bacteria such as *Escherichia coli*, and bioluminescence can be observed in a totally dark room when the cultures are 18 to 24 hours old. The biosafety level is established as BSL-1, requiring basic safety procedures and no special equipment or design features. Cleaning the work area with disinfectants, washing hands and not leaving them with an area with food is appropriate. To dispose, after submerging them with alcohol or bleaching overnight,

and discarding them with regular solid waste is recommended. They do not create a threat to the environment after they die, they can be disposed safely (Hauser, 2006).

2.7 Critical Analysis of Literature Review

Bioluminescence creates a foundation of possible light design opportunities for the built environment in architecture. The circadian rhythm of dinoflagellates proposes to be a better light source at night. With proper stimulations and amount, enough light can be gathered from some species. In addition, reviewed literature showed that depending on the biological clock, dinoflagellates can produce bioluminescent light without stimuli, which creates a great opportunity as a natural light source at night without additional energy required for stimulation. The bioluminescent bacteria do not need stimulation to produce light, however, they have a quorum sensing feature that allow them to be bioluminescent only if there are certain amount of bacteria species in the environment. This can mean that as long as there is certain amount of bacteria in the environment, bioluminescent light can be seen without additional energy required for stimulation.

The literature review shows that environmental factors such as temperature conditions, pH, and certain liquid media are essential for bioluminescent algae and bacteria. These environmental factors need to be controlled to tune the optimal flash characteristics and cell response. This situation can create maintenance issues, and for this reason, the integration of bioluminescent algae in the buildings can be location-oriented.

From conventional incandescent light bulbs to LED lamps, characteristic differences in light sources make them appropriate for different lighting purposes. LED lamps are among the most widely used ones for interior design purposes in architecture because of their efficiency and high lifespan features. Compared to other sources, bioluminescent light has a ‘cold light’ property, which indicates that produced light has a minimal amount of radiant heat emission. The color of bioluminescent light is

also another factor that may differ from the traditional light sources. Dinoflagellates show blue light and bioluminescent bacteria show blue-green light whilst there are different color options for traditional lights. Additionally, bioluminescence is a biological and natural light source, while the other light sources use a certain amount of electricity to produce light. However, at this point, it should be pointed out that maintaining the technology needed for bioluminescent light may also need a certain amount of energy.

The topics of the previous research in the literature have been mainly seemed to concentrate on the possible usage of these species in other fields. In the literature, there are also a number of conceptual studies related to the usage of bioluminescence in architecture. In addition, there are several projects, installations and exhibitions. However, there is not any study which focuses on simulating and visualizing the bioluminescent light for the usage in building interiors. At this point, the aim is to contribute to the literature by evaluating the bioluminescence for use in building interiors.

CHAPTER 3

MATERIALS AND METHOD

The materials and the method of this study are presented in this chapter under two sections separately. In the materials section, information sources, selected bioluminescent algae species for light production, selected building for case study, instrument for lighting measurements, software for lighting simulations and instruments for filter experiment are described. The steps of this research are explained in the method part.

3.1 Materials

The materials of this research are information gathered from related books, articles, conference proceedings and websites for selection of bioluminescent species, a case study building located in Ankara, a simulation software used for lighting simulations, a computer program for calculations, a digital lux meter for lighting measurements, a LED light for the filter experiment, acetate sheets and the data collected from the measurements. In the following paragraphs, the materials were explained in detail.

The characteristics of bioluminescent light, which is the subject of this research, can vary between the strains and the species. Therefore, defining the subject materials for selected bioluminescent species in the built environment is important. Based on the characteristics of microalgae species and their light amount, one species was selected in view of this research target to gather bioluminescent light.

3.1.1 Selected Species for Bioluminescent Lighting

In the literature, *Pyrocystis, Lingulodinium polyedrum, Pyrodinium, Ceratium* and *Ceratocorys horrida* are the most studied bioluminescent algae species. From

bioluminescent bacteria, *Vibrio fischeri* and *Vibrio harveyi* are the ones frequently mentioned. However, according to the previous works, bioluminescent dinoflagellates have higher bioluminescent light levels than bioluminescent bacteria. For this reason, bioluminescent algae was selected for use. The most frequently studied five dinoflagellate species were chosen and lumen amounts of traditional light sources and algae species' sample quantity needed to reach the same amount of light in lumen were investigated to establish a comparison (Table 3.1).

Table 3.1 Bioluminescent algae species and the sample quantity needed for gathering the amount of light produced by conventional light sources in the lumen (based on information from Veron, 2013).

Traditional Light Sources						
Algae	Bike Lamp	Clear incandescent 40 watt lamp	Incandescent 100 watt lamp	Fluorescent 36 watt lamp	Mercury vapor lamp	High pressure sodium lamp
	18 lm	430 lm	1380 lm	3000 lm	22000 lm	47000 lm
Ceratium	1,33 L	31,73 L	101,85 L	221,40 L	1623,62 L	3468,63 L
Ceratocorys	0,45 L	10,76 L	34,54 L	75,1 L	550,69 L	1176,47 L
Lingulodinium	0,001 L	0,025 L	0,08 L	0,175 L	1,285 L	2,75 L
Pyrocystis	0,0013 L	0,032 L	0,102 L	0,223 L	1,640 L	3,504 L
Pyrodinium	0,012 L	0,295 L	0,946 L	2,057 L	15,087 L	32,232 L

It can be seen that the required amount is less for the species of *Lingulodinium* and *Pyrocystis*, which means that these species produce higher amounts of lights than the others. On the other hand, the highest amount of sample needed to achieve the intended light quantity belongs to *Ceratium* species. *Lingulodinium polyedrum* was mentioned in the literature as that can be harmful, as it is one of the red tide creating dinoflagellates. However, *Pyrocystis* is known to be very common around the world, and from the case studies it is seen that mostly *Pyrocystis fusiformis* species have been cultivated for commercial purposes by companies, making these species easier to access and maintain. In addition to that, information related to the toxicity of

Pyrocystis fusiformis could not be found and it can be accepted as harmless for the utilization in the building interiors. For this reason, *Pyrocystis fusiformis* was selected for the integration of bioluminescence in the building interiors. The classification of the species was shown in the Table 3.2.

Table 3.2 Selected bioluminescent Pyrocystis fusiformis species and the biological classification (Guiry, 2018).

Classification of Pyrocystis fusiformis	
Empire	Eukaryota
Kingdom	Chromista
Subkingdom	Harosa (supergroup SAR)
Infrakingdom	Halvaria
Phylum	Miozoa
Subphylum	Myzozoa
Infraphylum	Dinozoa
Superclass	Dinoflagellata
Class	Dinophyceae
Order	Gonyaulacales
Family	Pyrocystaceae
Subfamily	Pyrocystoideae
Genus	Pyrocystis

The selected species are mostly photosynthetic; they have the ability to use sunlight and carbon dioxide to create energy-rich organic compounds. *Pyrocystis fusiformis* reported being found in Adriatic Sea, Black Sea, Canary Islands, Baja California, Portugal, Mexico (Pacific), Egypt, Brazil, Colombia, India, Taiwan, China and Australia (Guiry, 2018). These species were also included in the phytoplankton list of Turkey (Koray, 2001).

Pyrocystis fusiformis has a fusiform-shaped cell with size of approximately 970 x 163 μm. The number of flashes cell^{-1} is 23-62 and the maximum flash intensity is 690 x 10^9 photons s^{-1} (Latz et al., 2004). The wavelength of flashes varies between 412 nm and 553 nm and peaks around 470 nm, which is in the blue spectrum of light. The flash durations were observed in the 1000 msec and 9000 msec time period (Arneson et al., 1988). For growth or maintenance, the optimum temperature is

around 20-24 ºC (Latz et al., 1994). Reproduction occurs asexually, and cell division usually happens in the night phase with a minimum of 5 to 6 days time period (Sweeney, 1982).

Table 3.3 shows the luminous flux values of *Pyrocystis fusiformis* depending on the milliliter ratio. These values are the basis of applied bioluminescent lighting for the lighting simulations of this study. Different milliliter and liter amounts were calculated based on these ratios.

Table 3.3 Milliliter ratios and equivalent lumen values of Pyrocystis fusiformis (Veron, 2013).

Species	Milliliter ratio	Lumen amount
Pyrocystis	3 ml	40.24
	100 ml	1341.17
	250 ml	3352.93
	500 ml	6705.86
	1 L	13411.73
	5 L	67058.64
	10 L	134117.28

3.1.2 Selected Building for Case Study

The selected building is located in the 100. Yıl İşçi Blokları residential area in Ankara, Turkey. There are two types of buildings in the neighborhood: high-rise and low-rise. The selected dwelling is one of the high-rise buildings in the neighborhood, which is called 14th block. This dwelling is one of a typical case of high rise buildings in the area. The high-rise buildings have 15 floors and the examined floor for lighting measurements is the 13th floor. The building's entrance is on the southwest and the circulation axis is located southwest and northeast direction. Figure 3.1 shows the selected 14th block building. This building and the 13th floor is where the author's residence is located and the selected flat is a typical flat of high rise buildings. For these reasons, the building and the flat was selected.

Figure 3.1. The selected building called 14th block building in Ankara, Turkey.

There are four flats on each floor. At both ends of the circulation area, there are windows gathering sunlight from southeast and northwest directions. In the northwest part, there is an elevator shaft. There are two tones of colors for the paint in the circulation area. The artificial lighting is provided by the motion-activated luminaires, which have also light sensor that is sensitive to the light amount of the area. The measurements were conducted in the circulation area and in the selected flat. The selected flat for the interior lighting measurements and simulations is located in the southwest part of the building. Southwest direction is one of the most light gathering directions, and due to being the author's flat, the selected flat is appropriate for day and night light measurements conducted for 24 hours. Therefore, none of the residents of the other flats were disturbed during the lighting measurements. Figure 3.2 demonstrates the typical floor plan scheme of the building and the selected flat with color coding.

Figure 3.2. Architectural plan of a typical floor of the 14th block building consisting of four flats and the selected flat on the 13th floor with color coding where the lighting measurements and simulations were done.

As it can be seen, there are openings from the corridor to the living room, the entrance to the kitchen and the kitchen to the balcony.

3.1.3 Software

In this study, DIALux Evo lighting design program was used. As mentioned in the literature, the software calculates and visualize daylight and artificial light. For artificial lighting, the software has an electronic database of luminaires called LUMsearch from different manufacturers. It is an online platform with a luminaire search engine which allows users to get product information from photometry and

product properties to dimensional sketches and applications. In this research, the luminaires were selected with the help of LUMsearch and used for the lighting design.

Light sources, light source color filter, and spectral light reflectance factor curves are taken into account in DIALux, starting with version 4.3. There are different options in color temperatures of the light source and lamp types for users. Color filters are divided into four groups: color effect filter, color correction filter, high temperature filter and stage lighting, and each group has many filters within itself (Çelebi, 2007). In the study, filters were used for bioluminescent lighting.

The calculations done by DIALux are based on international and national standards such as EN12464, ISO 8995, EN1838 and EN13201. By the accredited lighting laboratory of DIAL, the results are tested and validated with international standards (CIE 171:2006) (Davoodi et al., 2014).

This study used the latest version of DIALux Evo (10.0). Specifications were taken into account according to EN 12464-1:2011, EN12454-2:2014, EN15193:2008, DIN V 18599:2007, CIE 97:2005 and CIE 154:2003 on the software.

3.1.4 Lux Meter

In this study, Roline Ro-1332 Digital Lux Meter was used, which is an instrument manufactured by Rotronic AG (Bassersdorf, Switzerland) for measuring illuminance in the field. The light-sensitive component is a silicon diode. With a photocell, it captures light and then converts this light to an electrical current. Measurement of this current allows the instrument to calculate the lux value of the light that is captured (Cambridge Building Energy & Environment Portal, n.d.).

The digital lux meter used for the measurements indicates 200 lux, 2000 lux, 20.000 lux and 200.000 lux ranges, respectively. Calibration for the meter is with the standard incandescent lamp at color temperature 2856 ºK. The meter has a data-hold function for measuring values. When hold mode is selected, the illuminance meter

stops all further measurements. The resolution is 0.1 lux, the measuring rate is approximately 2.0 times per second, the accuracy class is 3%, 0.5% and the repeatability is 2%. The meter is able to operate between 0 ºC and 40 ºC with 0 to 80% relative humidity. For power source, the instrument needs to have one 9 Volt battery (Roline, n.d.). Figure 3.3 shows the digital lux meter used in this study.

Figure 3.3. Roline RO-1332 Digital Lux Meter.

3.1.5 Portable LED Lamp

SONEXS 480L LED light (Figure 3.4) is a portable light source with 48 bright LED lights 8x18x8 cm in size. It uses a chargeable 6V battery and has two light intensities. Low level light is produced by turning on half of the LEDs and high level light is produced when all LEDs are on. The lamp was used in combination with blue colored acetate sheets to imitate the blue light from the algae.

Figure 3.4. SONEXS portable LED light lamp.

3.1.6 Acetate Sheets

Two different colors of transparent acetate sheets were used: dark and light blue; measuring 21 x 29.7 cm in size. In Figure 3.5, acetate papers used in this study were shown.

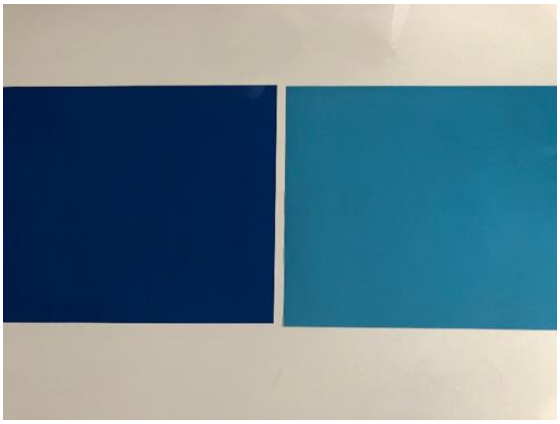


Figure 3.5. Dark blue and light blue acetate sheets.

3.2 Method

In order to evaluate the bioluminescent light in building interiors, gathered data from literature related to the light amount of bioluminescent species, lighting measurements and computer-based lighting simulations were used for the selected building interiors. The study aimed to investigate the usefulness of bioluminescence in building interiors and evaluate the possible usage of bioluminescence in common and private areas in a residential building. With this aim, the study was conducted to evaluate the integration of bioluminescent light in a residential building. In this regard, the methodology was shaped under ten steps, which were as follows:

Step 1: Gathering information related to the light amount of bioluminescent dinoflagellates and bioluminescent bacteria from the literature review and identifying the appropriate species for use.

Step 2: Gathering drawings and information related to the selected case study building from the management of the building. According to the drawings, the floor plans of the selected building and the flat were redrawn with color coding, as shown in Figure 3.2. The 3D models for simulations were done based on these plans.

Step 3: Taking lighting measurements from the selected interior spaces of the case study building for every hour during a 24-hour period by using Roline RO-1332 Digital Lux Meter (Figure 3.3). In Figure 3.6 the spaces and measurement points were demonstrated. These measurements were used to define the existing lighting condition.

Step 4: 3D modeling of the selected flat in DIALux as shown in Figure 3.7. The model was done by using tools in the software and paints in the interior spaces were applied from the color palette of the software as real-life case. In Table 3.4, details of the selected colors were given.

Step 5: Simulating the existing lighting condition of the selected interiors of the case study building with the help of DIALux software. Luminaires for the current scenario

were determined and chosen from LUMsearch and applied to the model. Table 3.6 presents the information about selected luminaires. The real-life measurements were converted to lumen from lux and used in the simulation of existing lighting condition.

Step 6: Comparing the lighting measurements with simulation results in order to calibrate the results of the software with real life measurements.

Step 7: Designing the bioluminescent light integrated condition. Luminaire for representation of bioluminescent light photobioreactors were selected from LUMsearch as seen in Table 3.6. The filter experiment was conducted by using SONEXS 480L portable LED source (Figure 3.4) and blue acetate sheets (Figure 3.5). Tests were made in the simulation with filters from DIALux to determine a blue filter for bioluminescence. According to the results and gathered information related to the characteristics of bioluminescent light through literature review, selected luminaires for bioluminescence were modified. The placement of bioluminescent lighting was determined considering spaces, target values and usability.

Step 8: Simulating and visualizing bioluminescent light and analyzing the measures done with DIALux software.

Step 9: Comparing the data obtained from the existing lighting condition and bioluminescent light integrated condition.

Step 10: Evaluating the results obtained from the simulations.

3.2.1 Measuring Lighting Conditions

Lighting measurements were done on the 13th floor of the selected building. The circulation area of the floor and every room of the selected housing unit were measured every hour throughout 24 hour-period. In 9 days, the 24-hour period was completed, and the measurements were also done at night time by staying awake until the morning. The measurements were done in winter time to observe the darkest

period. The details related to the dates and the hours were shown with the results in the next chapter.

The measurements were separated into two categories; ‘Level of artificial light’ and ‘Level of natural light’. In the Level of artificial light category, the amount of light that is produced by the installed artificial light was measured in lux units using the digital lux meter. In the Level of natural light, the amount of natural light during the light cycle period of the day, and the amount of light in the area without artificial light during the dark cycle period of the day were measured. For the hours of the day when the natural light was higher than the artificial light and there was no need to use an artificial light source such as 1 pm, the measurements for the ‘Level of artificial light’ category were not taken into consideration.

The measurements were conducted on the same selected measurement points in that 24-hour period. The Figure 3.6 shows the selected measurement points and the positions. Measurement points were selected based on the placement of the artificial lights. In areas with no artificial light installed, approximately the middle point of the room or the area was chosen as the measurement point. The photodetector of the digital lux meter was faced the light source horizontally. The distance to the light source was determined as 100 cm for the conversion of unit outputs. The height of the rooms is 280 cm and the lighting fixtures have approximately 30 cm distance from the ceiling. For this reason, the ground clearance was determined as approximately 150 cm. The simulation work plane was set at 150 cm as well, for the calibration with the simulation outputs. For the fixtures which do not have 30 cm length from the ceiling, second measurements were conducted. The first measurements were taken 100 cm away from these light sources, and the second measurements were taken from 150 cm for the calibration with the simulations. The measurements were done by placing the photodetector horizontally under the installed artificial light on the selected measurement point and the results were noted for each point and each hour until the 24-hour period was completed. When the numbers demonstrated on the screen of the digital lux meter started to stabilize, data hold functions were used and the results were noted. The door of the measuring

rooms was closed and the other unwanted light sources were turned off during the measurement in order to get precise results. While taking the measures, the lights of the other rooms were also closed. The data obtained from these measurements created a basis for the lighting simulations of the current condition.

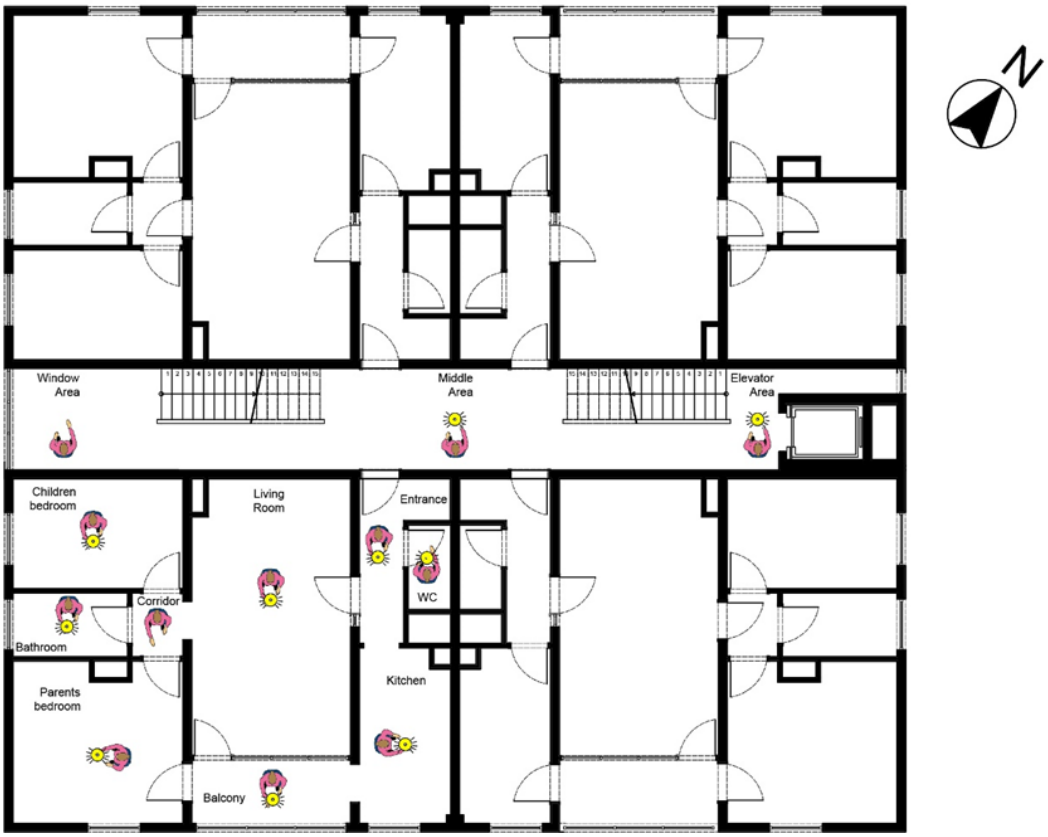


Figure 3.6. The placement of current lighting fixtures and measurement points.

3.2.2 Lighting Simulations

Lighting simulations were done with the help of Dialux software. Using the plan of the selected apartment, the 3D model of the apartment was created in the software by using the architectural elements. The colors of the rooms from the actual

apartment were determined and selected from the color palette of the software to apply. The details of the colors selected for the rooms were mentioned below in the Table 3.4. The paints in the circulation area were applied as one color for simplicity and clear results.

Table 3.4 RGB Values, reflection factor and reflective coating of the rooms inside the selected apartment.

ROOMS	**Child bedroom**	**Living room walls 1**	**Living room wall 2**	**Parents' bedroom**
RGB Values	R: 240	R: 240	R: 128	R: 240
	G: 21	G: 235	G: 128	G: 235
	B: 71	B: 221	B: 128	B: 221
Reflection Factor	18%	75%	19%	75%
Reflective Coating	0%	0%	0%	0%
ROOMS	**Entrance**	**Corridor**	**Balcony**	**Kitchen**
RGB Values	R: 240	R: 240	R: 255	R: 219
	G: 235	G: 235	G: 255	G: 218
	B: 221	B: 221	B: 255	B: 195
Reflection Factor	75%	75%	90%	62%
Reflective Coating	0%	0%	0%	0%
ROOMS	**WC**	**Bathroom**	**Circulation area**	
RGB Values	R: 219	R: 19	R: 255	
	G: 218	G: 196	G: 205	
	B: 195	B: 229	B: 162	
Reflection Factor	62%	41%	61%	
Reflective Coating	0%	0%	0%	

The circulation area of the 13th floor of the building was included in the lighting measurements. The length of the circulation area covers two flats on one side of the floor, and lighting measurements were done in one of the flats. For this reason, two mirrored apartments were included in the model with the circulation area; however, only one apartment, which the light data was taken from, was simulated. The

furniture inside the apartment was not included in the simulations. Floor coverings were not included as they are covered with carpets which were also considered as furniture. In Figure 3.7 3D model for the simulations can be seen.

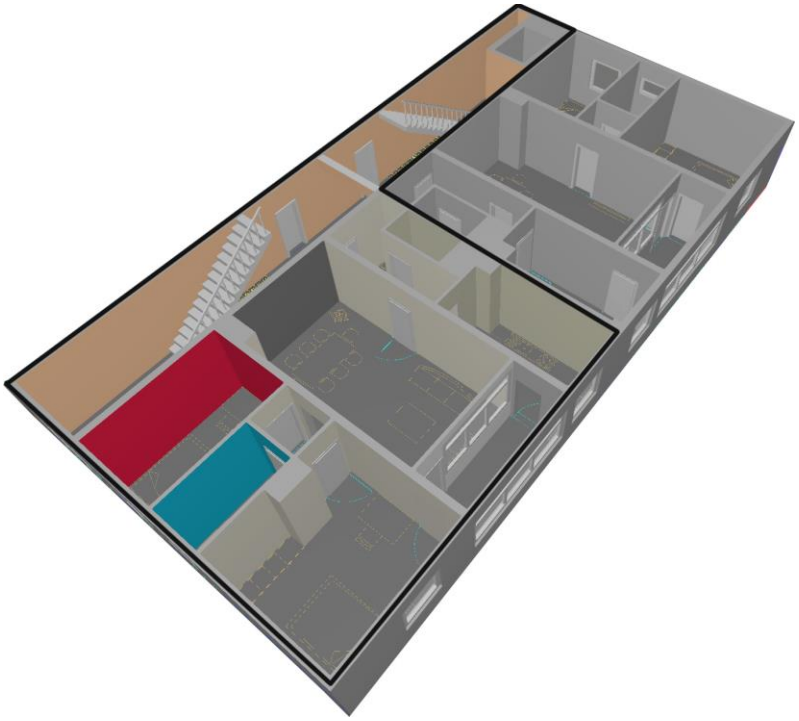


Figure 3.7. 3D view of the model showing the common circulation area and the selected apartment.

Spaces were identified and named based on the function of the room. The properties and utilization profile of the spaces for the lighting calculation was set from the categories defined by the DIALux based on the function of the spaces. The height of the spaces was modeled as 280 cm. The work plane height, which is the height of the measurement area for calculation, was determined as 150 cm since the lighting measurements were mostly taken from 150 cm due to being 100cm close to the light sources for unit conversions. The spaces with minimum illuminance requirements were given in Table 3.5.

Table 3.5 Illuminance requirements of the spaces

Illuminance requirements of the spaces					
Room	**Space**	**Function**	**Illuminance values (lux)**		
			Visual task	**Surrounding area**	**Background area**
Kitchen	Restaurants and hotels	Kitchens	500	300	100
WC	Rest, sanitation and first aid rooms	Cloakrooms, washrooms, bathrooms, toilets	200	150	50
Entrance	General Areas	Entrance halls	100	100	33.3
Balcony	Traffic zones inside buildings	Circulation areas and corridors	100	100	33.3
Living Room	Rest, sanitation and first aid rooms	Rest rooms	100	100	33.3
Parent's Bedroom	Rest, sanitation and first aid rooms	Rest rooms	100	100	33.3
Corridor	Traffic zones inside buildings	Circulation areas and corridors	100	100	33.3
Bathroom	Rest, sanitation and first aid rooms	Cloakrooms, washrooms, bathrooms, toilets	200	150	50
Children's Bedroom	Rest, sanitation and first aid rooms	Rest rooms	100	100	33.3
Circulation area	Traffic zones inside buildings	Circulation areas and corridors	100	100	33.3

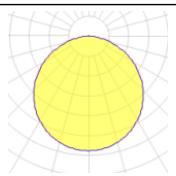
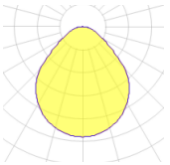
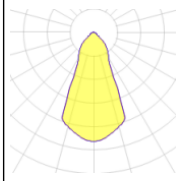
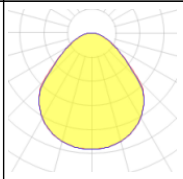
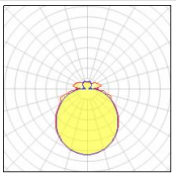
The lighting fixtures were selected from the luminaire catalogue of the DIALux called LUMsearch, which is an online catalogue where manufacturers upload their lighting fixtures and the data of the products. The selection of the luminaires from the catalogue was done based on the mounting mode and the sizes and the diameters of the current interior lighting fixtures. The software allows lumen amount, lamp type and the color features to be modified; however, selected luminaires are not allowed to be modified in size. In addition to that, the exact luminaires of the existing situation cannot be found in the catalogue; for that reason, appropriate luminaires were determined by the size and the mounting mode of the current lighting fixtures. Halogen light bulbs with a standard incandescent lamp spectrum were used in the luminaires.

The data from lighting measurements was used in the simulations for the existing lighting condition. The highest and lowest lux values from the lighting measurements were gathered and converted to lumen. The converted values were implemented to the selected luminaires. Data obtained from the simulations were evaluated by taking into account the target values set by the DIALux software. After gathering data related to the existing lighting condition, a comparison was established between the simulation results and the lighting measurements to calibrate the results. In order to check the effect of mirrors which create differences between the real-life lighting measurements and the simulations, a control measurement were done in the parent's room by covering the mirror, and the results were evaluated.

The lighting fixture for integration of bioluminescent light was also selected from LUMsearch database. The selection criteria of the fixture for bioluminescent lighting can be explained under four specifications. Bioluminescent algae require salty water medium to survive, oxygen supply and renewal of water. These requirements created basic principles for photobioreactors. For this reason, based on photobioreactors, a lighting fixture was chosen to represent bioluminescent light reactors in the simulations. Secondly, since the bioluminescent light is diffuse, the selected fixture has diffuse light output. The other selection criteria are related to the diffuse light by bioluminescence. Diffuse light is not efficient over 3 m heights above floor level due to dispersed illumination. Therefore, the bioluminescent light was integrated on walls at eye level to increase the efficiency with wall mounted fixtures. Lastly, the size of the fixture should be appropriate to carry large quantities of water, meaning that the selected fixture should be one of the largest ones in the database. According to the limitations in the database and the criteria for selection, a suitable lighting fixture was selected. The lighting fixture was modified in light amount and light color to represent the bioluminescent light by using the data collected from the literature review, experiment and tests. Table 3.6 demonstrates the information related to the selected lighting fixtures. The first four luminaires were used for the existing lighting condition. The number 1 was used in the living room, number 2 in the WC and bathroom, number 3 in bedrooms, kitchen and entrance, and the number

4 was used in the circulation area and the balcony. The luminaire number 5 is the one chosen for representation of bioluminescent lighting.

Table 3.6 Selected luminaires and information related to light output, mounting mode and measurements.

	Luminaire	Light Output	Mounting mode	Measurements
1			Ceiling mounted, pendant	Height: 64 mm Diameter: 780 mm
2			Ceiling mounted	Height: 75 mm Diameter: 300 mm
3			Pendant, Ceiling mounted	Height: 346 mm Diameter: 420 mm
4			Ceiling mounted	Length: 293 mm Width: 293 mm Height: 50 mm
5			Wall mounted	Length: 250 mm Width: 70 mm Height: 634 mm

3.2.3 Evaluating Blue Colored Light

Blue colored lighting conditions were tested in two ways: simulation and imitation. Firstly, blue light was evaluated by testing different blue filters in the simulation software to determine the blue spectrum of bioluminescence. In these simulations,

bioluminescent lighting fixtures were placed virtually on the wall near the staircase in the apartment building's circulation space, and 13 blue color filters selected from DIALux were tested. These color filters were applied to LED 3000 ºK, 4000 ºK, and 5500 ºK color temperatures of the chosen bioluminescent lighting fixture separately. Each combination was calculated with DIALux, and results were noted.

Then an experiment was conducted in the common circulation area to see the effect of blue color in real life by using SONEXS 480L LED light source (Figure 3.4) and two different blue-colored acetate sheets (Figure 3.5). The LED source was placed at 150 cm height on the wall near the window area in the circulation space, where the color filter tests in the simulation were also conducted, and lux measurements were taken with Roline RO-1332 Digital Lux Meter. Later, two acetate sheets were placed on the led source as filters separately, and the results of lux measurements were noted with each filter. Photographs of the wall and the ceiling were taken to visualize and compare the effect of blue filters with the simulations. Based on tests and experiment results, an appropriate color filter to use for the bioluminescent light integrated condition was determined.

The selected lighting fixture for bioluminescent lighting was modified in terms of lumen output and the color of light based on characteristics of bioluminescence. Lumen data gathered from literature was used, and the chosen blue color filter based on experiment and color filter tests was implemented. The placement of the bioluminescent light and the milliliter ratio of the algae was determined depending on target values, uniformity of the photobioreactors and possible usage. After designing the bioluminescent light integrated condition, the data were gathered from the simulations and visualizations were made to demonstrate the environment created with the bioluminescence. The bioluminescent light integrated condition was compared with the existing lighting condition, and evaluated for usability. The results and evaluations were given in the next chapter with discussion.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results of the lighting measurements conducted in the selected building, lighting simulations done for current condition and bioluminescent light integrated scenario were presented under different sections. The bioluminescent light integrated scenario was discussed and evaluated.

4.1 Lighting Measurements

Lighting measurements were conducted each hour for 24-hour in the common circulation area of the building's 13th floor, in the selected apartment's kitchen, entrance, WC, living room, children's bedroom, corridor, bathroom, parents' bedroom and balcony. Measured values with artificial light and without the artificial light were noted for each hour and for each architectural space. The findings were noted under the two categories; Level of artificial light and Level of natural light. As mentioned before, the measurements were conducted at the height of 150 cm. Secondary measurements were conducted from 100 cm close to the light source which do not have 100 cm distance between them and the lux meter when the measurements were conducted at 150 cm. The dates of the measurements and the related sunrise and sunset hours were given in Table 4.1. The hours after sunrise were referred as day hours, and the hours after the sunset were referred as dark hours.

Table 4.1 Measurement dates, sunrise and sunset hours.

Dates	Sunrise hours	Sunset hour
13.11.2021	07:31	17:34
14.11.2021	07:33	17:34
15.11.2021	07:34	17:33
6.12.2021	07:56	17:24
7.12.2021	07:57	17:24
9.12.2021	07:59	17:24
10.12.2021	07:59	17:24
11.12.2021	08:00	17:24
12.12.2021	08:01	17:24

4.1.1 Circulation Area

The measurements were conducted in the common circulation area of the 13th floor. The circulation area was divided into three parts; elevator area, middle hall and window area (Figure 4.1). Measurements were conducted on each part separately. Under the 'Level of artificial light' category, first and secondary measurements for the elevator area from 150 cm and 100 cm were shown. Table 4.2 demonstrates the results of the lux measurements taken from the elevator area, middle hall and the window area.

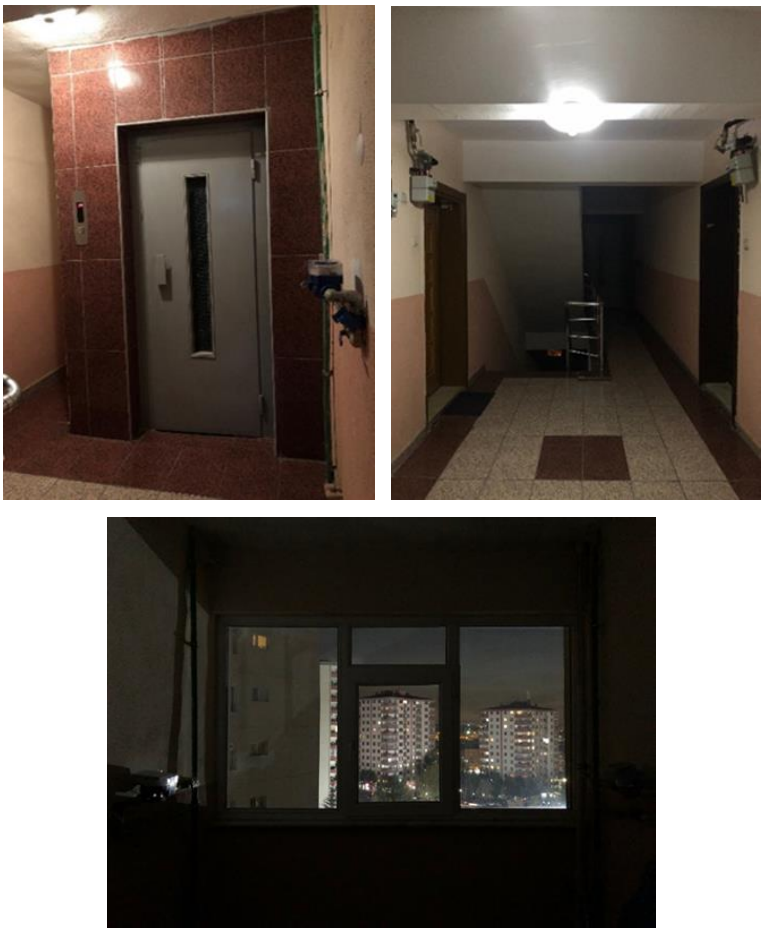


Figure 4.1. The parts of the circulation area. The picture on the left shows the elevator area, the picture on the right shows the middle hall area, and the picture on the below shows the window area.

The artificial light sources in the elevator area and middle hall have motion and light sensors. According to the movement, depending on the light amount in a specific time, the sensor activates and generates light. When the sensor did not activate by the movement due to the current light amount at that time, the measurements were not taken, and the results of the particular hours were demonstrated with the N/A symbol in Table 4.2. On the other hand, the window area did not have any artificial light source. For that reason, the category of Level of Artificial Light for the window area represents the light amounts in the area when the lights were on in the elevator area and the middle hall during dark hours. The results gathered during the day hours

in the Level of Natural Light category represent the light amount created by the sunlight on the measurement point. The results were noted for the window area in the Level of Natural Light category during dark hours when the lights were completely off in the circulation area. Similarly, the measurements for the dark hours for the elevator area and the middle hall were done while there was no other open light source.

Table 4.2 Lux measurements of the common circulation area.

14th block 13th floor circulation area lux measurements								
Date	Hour	Level of Natural Light (lux)			Level of Artificial Light (lux)			
		Elevator area	Middle hall	Window area	Elevator area (150 cm)	Elevator area (100 cm)	Middle hall	Window area
13.11.2021	06.00	0	0	0	50.9	81.7	44.9	0
14.11.2021	07.00	0	0	0.3	51.2	82.4	43.6	0.3
14.11.2021	08.00	3.6	2.3	280	N/A	N/A	44.6	280
14.11.2021	09.00	5.2	4.9	421	N/A	N/A	N/A	421
12.12.2021	10.00	9.5	6	479	N/A	N/A	N/A	479
7.12.2021	11.00	9.8	6.4	829	N/A	N/A	N/A	829
7.12.2021	12.00	11.8	9.6	1350	N/A	N/A	N/A	1350
12.12.2021	13.00	12.8	8.3	937	N/A	N/A	N/A	937
12.12.2021	14.00	15	7.8	610	N/A	N/A	N/A	610
7.12.2021	15.00	15.9	13.8	1032	N/A	N/A	N/A	1032
15.11.2021	16.00	11.8	19	1780	N/A	N/A	N/A	1780
15.11.2021	17.00	1.4	2.7	206	41.0	75.9	N/A	206
13.11.2021	18.00	0	0	0.1	45.8	71.5	48.6	0.2
13.11.2021	19.00	0	0	0.8	43.9	74.7	44.8	1
13.11.2021	20.00	0	0	0.8	48.9	75.0	43.7	0.9
13.11.2021	21.00	0	0	1	45.6	76.4	45.4	1.1
13.11.2021	22.00	0	0	0.9	49.4	77.7	47.3	1
13.11.2021	23.00	0	0	0.8	50.9	76.4	48.3	0.9
13.11.2021	24.00	0	0	0.8	48.2	76.3	44.3	0.9
14.11.2021	01.00	0	0	0	42.8	79.7	45.7	0
14.11.2021	02.00	0	0	0	49.4	80.6	48.5	0
10.12.2021	03.00	0	0	0	46.9	78.9	40.8	0
10.12.2021	04.00	0	0	0	44.6	79.9	34.0	0
10.12.2021	05.00	0	0	0	45.7	77.5	35.3	0

The data collected from the measurements shows that the window area gets significantly more sunlight during the day hours than the elevator and middle hall areas. This finding is important because the algae need sunlight to photosynthesize. This information guides the decision of placement of the algae. In the window area,

during the dark hours, a dim light was measured, even though the measurements were done without any active artificial light inside the circulation area for the Level of natural light category. The reason of this is the light coming from the astroturf pitch which is near the building. Figure 4.2 displays the light sources of the nearby astroturf pitch.

Figure 4.2. Light coming into the common circulation area through the window overlooking the neighboring astroturf pitch when the lights are on.

According to the values under the Level of Artificial Light category, it can be seen that the light sensor did not activate between 8 am and 4 pm in the elevator area. In the middle hall, the light sensor did not generate light between 9 am and 5 pm. There is a slight change in the amount of light in the window area when the middle and elevator area lights are open; however, it can be seen that the current light sources are not enough to lighten the window area.

4.1.2 Residential Interiors

The measurements in the interiors of the selected flat were conducted in every room. The spaces were described as parent's bedroom, children's bedroom, bathroom,

corridor, living room, entrance, kitchen, WC, and balcony. For the Level of Natural Light, the measurements were conducted when there was no open artificial light. The doors of the room where measurements were taken were closed in order not to affect the data by the light coming from other rooms. In the spaces where the sunlight is stronger than artificial light, and there is no need for artificial light to lighten the room, between 9 am and 3 pm, the measurements for the Level of Artificial Light were not taken. After 3 pm, the rooms usually started to be dark without the artificial light. For that reason, the measurements were done with artificial light from 4 pm until the 8 am.

Table 4.3 shows the data collected from bedrooms. The results taken from the bedrooms show that during day hours, the parent's bedroom gets more sunlight than the children's bedroom. In addition to that, the lux amounts measured in the children's bedroom with the artificial light during the dark hours are lower compared to the parent's bedroom.

Table 4.3 The results of the lux measurements taken from bedrooms.

Date	Parent's bedroom			Children's bedroom		
	Hour	Level of Natural Light (lux)	Level of Artificial Light (lux)	Hour	Level of Natural Light (lux)	Level of Artificial Light (lux)
10.12.2021	06.00	0	191.0	06.00	0	79.5
10.12.2021	07.00	0	177.2	07.00	0	74.5
11.12.2021	08.00	3.8	182.5	08.00	1.8	81.8
12.12.2021	09.00	377	Not Measured	09.00	38.1	Not Measured
12.12.2021	10.00	174.4	Not Measured	10.00	51.2	Not Measured
7.12.2021	11.00	873	Not Measured	11.00	83.1	Not Measured
7.12.2021	12.00	707	Not Measured	12.00	131.5	Not Measured
12.12.2021	13.00	641	Not Measured	13.00	110.2	Not Measured
12.12.2021	14.00	191	Not Measured	14.00	98.8	Not Measured
7.12.2021	15.00	80.2	Not Measured	15.00	107.1	Not Measured
7.12.2021	16.00	6	175.9	16.00	7.4	73.2
6.12.2021	17.00	8.6	174.2	17.00	27	102.8
6.12.2021	18.00	0	170.9	18.00	0	67.8
6.12.2021	19.00	0	157.5	19.00	0	70.7
7.12.2021	20.00	0	154.8	20.00	0	73.2
7.12.2021	21.00	0	152.7	21.00	0	71.6
7.12.2021	22.00	0	156.4	22.00	0	72.9
6.12.2021	23.00	0	163.5	23.00	0	76.8
6.12.2021	24.00	0	180.0	24.00	0	78.4
6.12.2021	01.00	0	185.0	01.00	0	78.5
9.12.2021	02.00	0	176.6	02.00	0	75.2
9.12.2021	03.00	0	161.9	03.00	0	72.2
9.12.2021	04.00	0	177.4	04.00	0	77.3
9.12.2021	05.00	0	175.5	05.00	0	69.1

Table 4.4 demonstrates the data collected from the bathroom and WC. The bathroom has noticeably higher lux amounts during the dark hours than WC. In the WC, it can be seen that in the Level of Natural Light section, the lux amount in the room was zero. The reason for this is that, there is no natural light coming to the room; the only light source is the artificial light. Hence, the measurements were done for the Level of Artificial Light section for 24-hour.

Table 4.4 The results of the lux measurements taken from the bathroom and WC.

Date	Bathroom			WC		
	Hour	Level of Natural Light (lux)	Level of Artificial Light (lux)	Hour	Level of Natural Light (lux)	Level of Artificial Light (lux)
10.12.2021	06.00	0	671.0	06.00	0	85.1
10.12.2021	07.00	0	647.0	07.00	0	82.7
11.12.2021	08.00	2.1	708.0	08.00	0	81.8
12.12.2021	09.00	51.2	Not Measured	09.00	0	73.7
12.12.2021	10.00	67.5	Not Measured	10.00	0	96.6
7.12.2021	11.00	95.4	Not Measured	11.00	0	67.6
7.12.2021	12.00	139.7	Not Measured	12.00	0	74.9
12.12.2021	13.00	220	Not Measured	13.00	0	72.8
12.12.2021	14.00	93.2	Not Measured	14.00	0	90.8
7.12.2021	15.00	140.7	Not Measured	15.00	0	76.6
7.12.2021	16.00	7.3	646.0	16.00	0	68.6
6.12.2021	17.00	23.3	620.0	17.00	0	66.6
6.12.2021	18.00	0	582.0	18.00	0	84.0
6.12.2021	19.00	0	606.0	19.00	0	74.6
7.12.2021	20.00	0	646.0	20.00	0	70.8
7.12.2021	21.00	0	627.0	21.00	0	85.8
7.12.2021	22.00	0	604.0	22.00	0	72.6
6.12.2021	23.00	0	629.0	23.00	0	70.7
6.12.2021	24.00	0	665.0	24.00	0	72.9
6.12.2021	01.00	0	697.0	01.00	0	94.2
9.12.2021	02.00	0	658.0	02.00	0	74.2
9.12.2021	03.00	0	689.0	03.00	0	71.7
9.12.2021	04.00	0	679.0	04.00	0	73.4
9.12.2021	05.00	0	674.0	05.00	0	72.8

Table 4.5 displays the lux values of the living room. The living room gets indirect sunlight from the balcony through the windows. The windows create visual connection with the balcony.

Table 4.5 The lux measurement results of the living room.

Date	Living Room		
	Hour	Level of Natural Light (lux)	Level of Artificial Light (lux)
10.12.2021	06.00	0	116.1
10.12.2021	07.00	0	116.7
11.12.2021	08.00	0.8	124.3
12.12.2021	09.00	91.6	Not Measured
12.12.2021	10.00	24	Not Measured
7.12.2021	11.00	224	Not Measured
7.12.2021	12.00	140	Not Measured
12.12.2021	13.00	96.3	Not Measured
12.12.2021	14.00	68.3	Not Measured
7.12.2021	15.00	19.5	Not Measured
7.12.2021	16.00	1.2	88.3
6.12.2021	17.00	1.8	100.9
6.12.2021	18.00	0	106.9
6.12.2021	19.00	0	88.9
7.12.2021	20.00	0	107.7
7.12.2021	21.00	0	107.5
7.12.2021	22.00	0	103.6
6.12.2021	23.00	0	109.1
6.12.2021	24.00	0	103.7
6.12.2021	01.00	0	105.1
9.12.2021	02.00	0	119.0
9.12.2021	03.00	0	122.4
9.12.2021	04.00	0	109.8
9.12.2021	05.00	0	108.5

The data gathered from the measurements of the kitchen was given in Table 4.6. The kitchen gets direct sunlight through windows.

Table 4.6 The results of lux measurements in the kitchen.

Date	Kitchen		
	Hour	Level of Natural Light (lux)	Level of Artificial Light (lux)
10.12.2021	06.00	0	54.7
10.12.2021	07.00	0	52.8
11.12.2021	08.00	7.1	55.3
12.12.2021	09.00	311	Not Measured
12.12.2021	10.00	243	Not Measured
7.12.2021	11.00	880	Not Measured
7.12.2021	12.00	890	Not Measured
12.12.2021	13.00	960	Not Measured
12.12.2021	14.00	467	Not Measured
7.12.2021	15.00	138.2	Not Measured
7.12.2021	16.00	6.3	58.4
6.12.2021	17.00	6	70.9
6.12.2021	18.00	0	62.5
6.12.2021	19.00	0	68.9
7.12.2021	20.00	0	51.4
7.12.2021	21.00	0	51.5
7.12.2021	22.00	0	52.7
6.12.2021	23.00	0	54.8
6.12.2021	24.00	0	43.6
6.12.2021	01.00	0	60.4
9.12.2021	02.00	0	54.4
9.12.2021	03.00	0	48.3
9.12.2021	04.00	0	49.7
9.12.2021	05.00	0	40.7

In Table 4.7, the results of the measurements done in the entrance and corridor were demonstrated. Despite not having natural light directly through windows, the entrance has illuminance during the day times presumably affected by the kitchen windows since there is no door between kitchen and entrance. Similarly, there was natural light in the corridor area during day times even though the doors of the parent's bedroom, bathroom and children's bedroom were closed. The natural light in the corridor was coming from the living room as there is not a door from the living

room to corridor. In the corridor area, there was no artificial light applied. Therefore, the measurements were not taken for the Level of Artificial Light category and displayed with N/A.

Table 4.7 The lux measurement results of the entrance and corridor..

Date	Entrance			Corridor		
	Hour	Level of Natural Light (lux)	Level of Artificial Light (lux)	Hour	Level of Natural Light (lux)	Level of Artificial Light (lux)
10.12.2021	06.00	0	133.3	06.00	0	N/A
10.12.2021	07.00	0	141.9	07.00	0	N/A
11.12.2021	08.00	0.1	145.8	08.00	0	N/A
12.12.2021	09.00	11.8	Not Measured	09.00	7.9	N/A
12.12.2021	10.00	7.6	Not Measured	10.00	1.6	N/A
7.12.2021	11.00	37.2	Not Measured	11.00	14.3	N/A
7.12.2021	12.00	31.6	Not Measured	12.00	9.5	N/A
12.12.2021	13.00	38.3	Not Measured	13.00	5.6	N/A
12.12.2021	14.00	20.8	Not Measured	14.00	3.9	N/A
7.12.2021	15.00	6.7	Not Measured	15.00	1.4	N/A
7.12.2021	16.00	0.3	127.7	16.00	0	N/A
6.12.2021	17.00	0.2	132.8	17.00	0	N/A
6.12.2021	18.00	0	111.0	18.00	0	N/A
6.12.2021	19.00	0	118.7	19.00	0	N/A
7.12.2021	20.00	0	123.7	20.00	0	N/A
7.12.2021	21.00	0	126.0	21.00	0	N/A
7.12.2021	22.00	0	122.1	22.00	0	N/A
6.12.2021	23.00	0	119.8	23.00	0	N/A
6.12.2021	24.00	0	146.6	24.00	0	N/A
6.12.2021	01.00	0	144.4	01.00	0	N/A
9.12.2021	02.00	0	133.8	02.00	0	N/A
9.12.2021	03.00	0	126.6	03.00	0	N/A
9.12.2021	04.00	0	139.1	04.00	0	N/A
9.12.2021	05.00	0	140.6	05.00	0	N/A

Table 4.8 shows the results of the measurements of the balcony. It can be seen that during the day hours, the balcony area is quite bright with natural light, which is a discriminating finding for the algae placement. The light source in the balcony does not have 30 cm length from the ceiling; therefore, the measurements done from both

150 cm for the simulation calibration and from the 100 cm for conversion of lumen value from lux values. Since 100 cm is closer to the light source, the lux amounts gathered from the secondary measurements are higher.

Table 4.8 The lux measurement results of the balcony.

Date	**Balcony**				
	Hour	Level of Natural Light (lux)	Level of Artificial Light from 150 cm (lux)	Hour	Level of Artificial Light from 100 cm (lux)
10.12.2021	06.00	0	41.6	06.00	65.0
10.12.2021	07.00	0	41.3	07.00	65.5
11.12.2021	08.00	77.9	122.6	08.00	132.4
12.12.2021	09.00	837	Not Measured	09.00	Not Measured
12.12.2021	10.00	1770	Not Measured	10.00	Not Measured
7.12.2021	11.00	25400	Not Measured	11.00	Not Measured
7.12.2021	12.00	29400	Not Measured	12.00	Not Measured
12.12.2021	13.00	30500	Not Measured	13.00	Not Measured
12.12.2021	14.00	27000	Not Measured	14.00	Not Measured
7.12.2021	15.00	1281	Not Measured	15.00	Not Measured
7.12.2021	16.00	62.2	100.4	16.00	121.2
6.12.2021	17.00	88.6	110.4	17.00	125.4
6.12.2021	18.00	0	43.6	18.00	67.1
6.12.2021	19.00	0	44.5	19.00	79.2
7.12.2021	20.00	0	38.0	20.00	63.5
7.12.2021	21.00	0	39.7	21.00	64.3
7.12.2021	22.00	0	39.2	22.00	65.4
6.12.2021	23.00	0	38.0	23.00	65.7
6.12.2021	24.00	0	41.0	24.00	76.3
6.12.2021	01.00	0	40.4	01.00	72.2
9.12.2021	02.00	0	38.4	02.00	62.5
9.12.2021	03.00	0	40.8	03.00	63.9
9.12.2021	04.00	0	42.0	04.00	66.8
9.12.2021	05.00	0	42.1	05.00	65.3

4.2 Conversion of Lux Measurements to Lumen Unit for Simulations

In order to simulate the existing lighting situation in the measured spaces, gathered data collected with the lux unit was converted to the lumen unit. DIALux software uses luminous flux (lumen) values of light sources for calculations. It gives the results of average illumination of space with lux values with the distribution of light in the calculated space.

There is a simple equation between the lux and lumen. As mentioned before, lumen (lm) measures the total light output of a source in the SI unit system. Lux is the measure of the quantity of light on a surface. The equation is as follows:

1 lumen = 1 lux * $1m^2$

According to the equation, meter square values of the spaces were calculated and multiplied by the measured lux values of the spaces. Two sets of calculations were done. First, the lowest value of the measurements for each space was put on the calculations. Second, the highest value from the measurements were taken for the calculations. The lowest and highest values were chosen among the measurements between 6 pm and 5 am. In Table 4.9, the lowest and highest lux values of the areas with related square meters and the results of the conversions of each measured space were displayed.

The lowest and highest lumen amounts of the areas were calculated with zero decimal places in order to use the numerical data in the simulations. The circulation area was split into two areas and therefore, square meter values were also divided into two. Since there was no artificial light in the corridor and window area of the circulation area, these spaces were not included in the table.

Table 4.9 Areas with measured light levels and calculated lumen values.

Spaces	Lowest Value of Lux Measurements	Highest Value of Lux Measurements	Meter square	Lowest Lumen Amount	Highest Lumen Amount
Elevator area (100 cm)	71.5	80.6	22.53	1611	1816
Middle hall	34	48.6	22.53	766	1095
Parent's bedroom	152.7	185	14.91	2277	2758
Children bedroom	67.8	78.5	10.42	706	818
Bathroom	604	697	4.06	2452	2830
WC	70.7	94.2	2.02	143	190
Living room	88.9	119	24.22	2153	2882
Kitchen	43.6	68.9	8.69	379	599
Entrance	111	146.6	5.12	568	751
Balcony (100 cm)	62.5	79.2	5.63	352	446

4.3 Lighting Simulations

After completing the lighting measurements, lighting simulations were conducted for the existing lighting condition and the bioluminescent light integrated condition to see the effect of bioluminescent light on the total light amount in the integrated area and the visual environment that bioluminescence creates in indoor spaces.

4.3.1 Existing Lighting Condition

Simulations for existing lighting condition were done by using highest and lowest lumen amounts. Numerical data were put in the properties of selected light sources for each space and calculations were done. Results were evaluated based on the target

value developed by DIALux according to the standards which were mentioned in previous chapters.

Table 4.10 shows the illumination amounts in the spaces after applying data of lowest and highest lumen amounts. In addition, recommended target values for minimum illumination defined by the spaces was indicated. The bathroom and parent's bedroom have higher illumination than the minimum target value in both cases. The entrance and the living room exceeded the target after applying the highest lumen values. In Figure 4.3, the simulation done with the lowest lumen was demonstrated.

Table 4.10 Results of the simulations of the existing lighting condition and target values.

Spaces	**Simulation results with lowest lumen values**	**Simulation results with highest lumen values**	**Target value for minimum**
Balcony	42.5	54.1	100 lux
Bathroom	380	438	200 lux
Children bedroom	56.8	65.7	100 lux
Circulation area	38.4	47.7	100 lux
Corridor	9.64	12.9	100 lux
Entrance	89.4	118	100 lux
Kitchen	37.1	58.4	500 lux
Living room	75.4	101	100 lux
Parents bedroom	134	162	100 lux
WC	40.8	54.2	200 lux

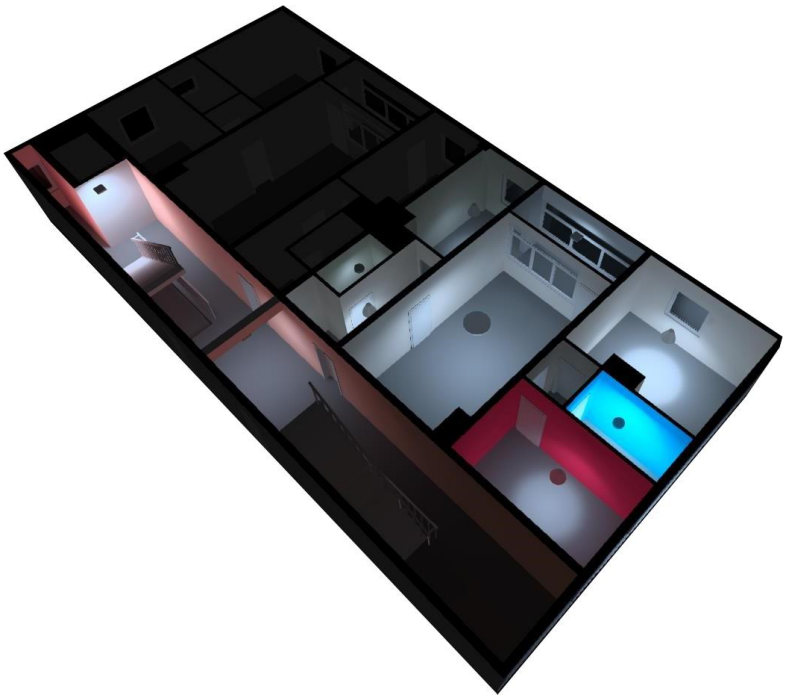


Figure 4.3. Render of the existing lighting condition done by using the lowest lumen amounts.

Subsequent to the simulations for the existing lighting condition, a comparison was made between the simulation results and lighting measurements to evaluate the overall results. The lighting measurements were conducted around 150 cm above the ground, and the calculation plane on the simulation was set 150 cm above the ground to calibrate the results. Table 4.11 displays the results of the simulations and the lighting measurements done for the spaces.

Table 4.11 Comparison of lux measurements and simulation results.

Spaces	Simulation results with highest lumen values	Highest value of lighting measurements (lux)	Simulation results with lowest lumen values	Lowest value of lighting measurements (lux)	Target value for minimum
Balcony	54.1 lux	41	42.5 lux	38	100 lux
Bathroom	438 lux	697	380 lux	604	200 lux
Children bedroom	65.7 lux	78.5	56.8 lux	67.8	100 lux
Circulation area	47.7 lux	Elevator area: 50.9 Middle hall: 48.6	38.4 lux	Elevator area: 42.8 Middle hall: 34	100 lux
Corridor	12.9 lux	0	9.64 lux	0	100 lux
Entrance	118 lux	146.6	89.4 lux	111	100 lux
Kitchen	58.4 lux	68.9	37.1 lux	43.6	500 lux
Living room	101 lux	119	75.4 lux	88.9	100 lux
Parents bedroom	162 lux	185	134 lux	152.7	100 lux
WC	54.2 lux	94.2	40.8 lux	70.7	200 lux

In Table 4.11, it can be observed that simulation results are slightly different than the lighting measurements. Results of simulations of balcony are slightly higher than the lighting measurements. On the other hand, results of lighting measurements done in the bathroom, children's bedroom, entrance, kitchen, living room, parent's bedroom and WC are higher than the simulation results of these spaces. The reason of this difference was thought to be the effects of the furniture, especially mirrors located in some of the rooms. In the bathroom, children's bedroom, entrance, living room, parent's room and WC, there are mirrors that may affect by increasing the reflection of light during the lighting measurements. Nonetheless, in simulations, furniture including mirrors were not included to get clear results. In the circulation area, the results are approximate. There was no light measured in the corridor area due to having no artificial light and closing the other lights of the rooms. However, in the simulation, the entire project is simulated with all the light scenes together. Therefore, the light coming from the living room to the corridor affected the lighting results in the simulations.

In order to check the effect of mirrors located in the rooms on the lighting measurements, a control measurement was done in the parent's room. The mirror in

the parent's room was closed, covered with a non-transparent sheet and lighting measurements were conducted in the same measurement point at 150 cm above the ground. The measurements were done from 7 pm to 7 am for every hour for a 12-hour period not to have any additional light from exteriors. Table 4.12 shows the results of the control measurements done in the parent's room and means values of the results gathered with mirror effect and without the mirror effect.

Table 4.12 Lighting measurement results done in Parent's bedroom with and without mirror effect..

Parent's bedroom		
Hour	Level of Artificial Light (Without Mirror Effect) lux	Level of Artificial Light (With Mirror Effect) lux
19.00	163.2	157.5
20.00	152.4	154.8
21.00	147.8	152.7
22.00	150.2	156.4
23.00	165.5	163.5
24.00	161.7	180.0
01.00	164.7	185.0
02.00	154	176.6
03.00	145.2	161.9
04.00	162.9	177.4
05.00	154	175.5
06.00	157.4	191.0
07.00	175	177.2
Mean Value of Lux Measurements	158.0	171.4

From the table, it can be seen that the mean values of the lighting measurements done by covering the mirror are lower than the results gathered with the mirror effect. For this reason, the difference between the simulations and the lighting measurements can be due to the mirror in the rooms and reflective furniture.

4.3.2 Simulating Bioluminescent Lighting

The placement of bioluminescent light was done based on the spaces, the target values and the usability. According to the simulations for the existing condition, the balcony, children's bedroom, circulation area, corridor, entrance, kitchen, living room and WC showed lower illuminance than the target value when the lowest lumen amounts were used. After applying the highest lumen amounts, the living room and entrance showed higher illuminance than the target. In the bioluminescent light integrated situation, the lowest lumen values were taken into consideration in order to get a better understanding of the amount of light needed and the effect of bioluminescent light in the darker scenario.

In the simulations, data related to the light amount of *Pyrocystis fusiformis* was gathered from previous studies due to not being able to take in vivo and in situ measurements of the bioluminescent species. In addition to that, no furniture, including carpets on the floor, was included in the simulations as limitations to get clear results.

As mentioned before, bioluminescent algae have a circadian rhythm that makes them glow mostly at night with stimulation and sometimes by themselves. For this reason, using bioluminescent algae in bedrooms may not be the best choice as they may start glowing in the middle of the night and disturb the sleeping cycle. In addition to that, the sound of the water of the bioluminescent algae during flow for the oxygen supply may not be appropriate for spaces that need silence. Therefore, even though the children's bedroom was lower than the target value in terms of lighting, bioluminescent light was not integrated to the bedrooms.

The kitchen requires more light, preferably natural light to increase the carefulness and awareness during any kind of activity. However, the blue color of bioluminescent light may affect the color of furniture and materials like a filter. This can create wrong choice of gadgets or difficulty with distinguishing foods.

Moreover, despite not being hazardous, bioluminescent algae are not recommended to be near the food. Hence, bioluminescence was not applied in the kitchen area.

As discussed before, bioluminescent algae cannot produce continuous light for hours. Depending on the cell amount, age of the cells, environment and the light cycle, the cells start to get exhausted after seconds to a few minutes. Due to exhaustion, the intensity of bioluminescence starts to decrease. Therefore, using bioluminescent light in spaces where occupants spend less time pass through to other places is more convenient. For this reason, bioluminescent light was not integrated to the living room, and it was placed in the circulation area, balcony, corridor, entrance and WC.

The bioluminescent light is diffuse and the light becomes less efficient as the distance from the light source increases. Hence, the bioluminescent light source was placed in the mid-height at around 150 cm for effective usage of the light.

The size of the luminaire which presents the bioreactor is 25 x 7 x 63.4 cm. The total volume of the whole bioreactor, which will carry the marine water with bioluminescent algae is approximately 11095 cm^3. Considering the fact that 1L equals 1000 cm^3, the photobioreactors integrated in the interiors can have up to 11 liters of bioluminescent media. However, since the system will need oxygen transportation, mechanical stimulation and agitation, there should be an empty space for the water and the system for the movement. Therefore, the maximum amount of medium for the algae was determined around 5 to 6 liters. In this way, approximately half of the volume was left for the movement of the water and the oxygen supply mechanisms.

The simulations were done by using different volumes of water. With the existing lighting appliances, various volumes were implemented. According to the trials, 500 ml was not enough to reach the target for most of the rooms; 2L was remarkably higher than the target. However, 1L of bioluminescent algae assured reaching the target for most of the rooms. To be able to provide uniformity in mL and bioreactors, 1L of algae was integrated into the rooms. Only in the circulation area and in the

entrance, with 1L of algae bioreactors, the target was not reached, and there should be more than one photobioreactor to place. In order not to place too many photobioreactors in the circulation area due to maintenance and cost-efficiency reasons, 5L was implemented to the photobioreactors in the circulation area, and with 2 photobioreactors, the target value was reached. In the two algae photobioreactors, 5L of medium was implemented. The target value was reached in the entrance area with one photobioreactor of 2L algae. In the simulations, 1L was applied as 13411 lumens, 2L 26822 and 5L 67058 lumens.

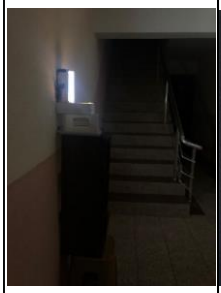
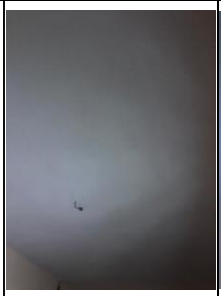
For determination of the blue color filter representing the bioluminescence's blue spectrum, filter tests in simulation were done in the circulation area. In the filter tests, two bioluminescent photobioreactors each with 5L of medium were placed on the window area wall of the circulation area. With LED 3000 ºK, 4000 ºK and 5500 ºK color temperatures of the chosen luminaire, which represents bioluminescent photobioreactors, 13 blue filters from the DIALux filter catalogue were tested. Each combination was calculated and rendered from the same camera angle. The combinations were evaluated, and calculations were compared with the existing situation of the circulation area. As the filter gets darker, the overall lux value decreases. The combinations can be seen in the appendix part.

4.3.2.1 Evaluating Blue Color Lighting

To determine the blue color filter for the bioluminescence, an experiment was conducted near the window area of the circulation space. At the same place on the wall where the bioluminescent light is intended to integrate, a light source, SONEXS 480L LED (Figure 3.4) was placed. The placement was done at 150 cm as the bioreactors. First, lux measurements when the light source was turned on were conducted at the same measurement point before in the window area without a filter. Pictures were taken to see the effect on wall painting and the ceiling. Later, light blue and dark blue acetate paper were placed on top of the light source separately. The lux measurements were done with each filter and the results were noted. In order to

understand how the filters interact with the existing colors of the circulation wall and the ceiling, pictures were taken. Table 4.13 demonstrates the experiment setup, results and the images taken from the experiment.

Table 4.13 Color filter experiment and the results.

Experiment Setup			
	Light source without a filter	Light source with light blue filter	Light source with dark blue filter
Setup			
Effect on wall painting			
Effect on ceiling			
Measured lux value	3.4	2.8	1.7

As seen in the table, when the filter gets darker, the measured lux value in the environment decreases. This finding matches the simulation filter tests. It was observed that when the darker blue filters were chosen, lux results in the simulations

decreased noticeably, and the darker blue acetate sheet represented the algae effect better.

According to the images from literature review, filter tests and experiment results, the appropriate filter combination for the simulation was chosen as 4000 °K with 075 filter, and applied all the bioluminescent light photobioreactors in the simulation.

4.3.2.2 Circulation Area

The bioluminescent light works as a guiding light for the occupants in the circulation area. In order to lighten the window area at night and guide the occupants through the stairs, the bioluminescent lighting was placed on the wall of the stair side, and placed back from the start of the stair to prevent any bumping during the usage of the stair. Two photobioreactors were placed in the circulation area based on the simulation results in order to reach the target value. Figure 4.4 shows the current condition of the window area and Figure 4.5 shows the bioluminescence integrated condition.

Figure 4.4. Existing lighting condition of the building's common circulation area in the day light.

Figure 4.5. The bioluminescent light in the building's common circulation area.

4.3.2.3 Corridor and Entrance

In the corridor and entrance, the bioluminescence helps users to pass to other rooms. In the entrance, the illuminance values were higher than the target value when the highest lumen values were applied, but the results stayed under the target value when the lowest lumen values were applied. Users spending less time in the entrance and using the space for passing through makes the entrance appropriate for the usage of bioluminescent light.

In the corridor, the bioluminescent light was placed on the wall near the entrance of the corridor. In the entrance, the bioluminescent light was integrated on the wall in front of the living room door to help occupants effectively while transit passing to WC or to the kitchen. Figure 4.6 demonstrates the current condition of the corridor and Figure 4.7 shows the bioluminescence integrated situation in the corridor.

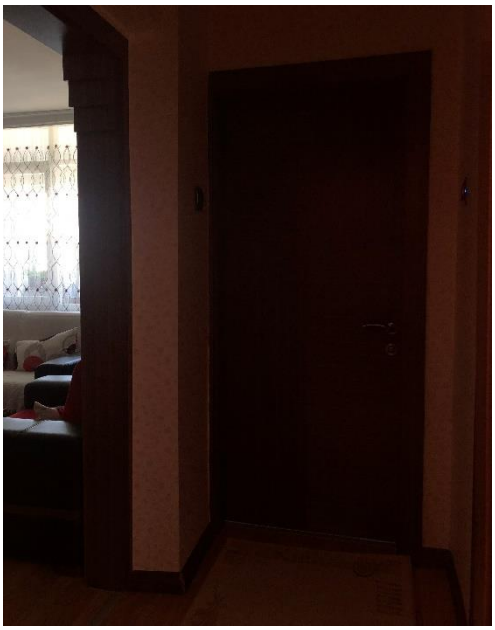


Figure 4.6. Existing lighting condition of the corridor in the day light.

Figure 4.7. The bioluminescent light in the corridor.

The occupants are expected to use the entrance only for passing purposes or for a short amount of time. Therefore, current artificial light was removed from the entrance after bioluminescent light was placed. The bioluminescence can enlighten the entrance for a short time, such as leaving the coat after coming home or passing to the WC from living room. In this way, the overall electricity load of the flat can

be decreased. However, with the 1L of algae, the target could not be reached in the entrance area without the artificial light. For this reason, the algae were implemented as 2L. The existing condition and bioluminescent light integrated condition of the entrance was shown in Figure 4.8 and Figure 4.9 respectively.

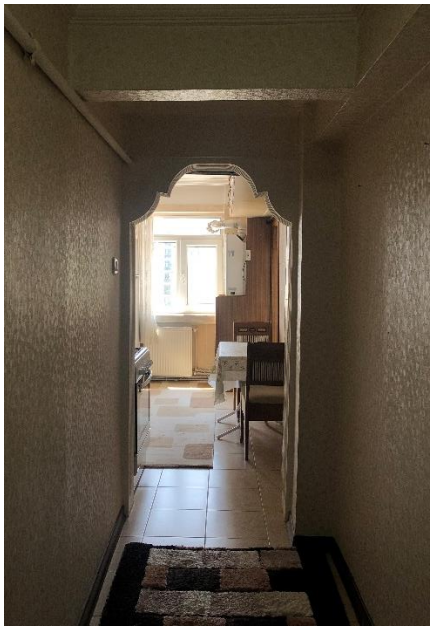


Figure 4.8. Existing lighting condition of the entrance in the day light.

Figure 4.9. The bioluminescent light in the entrance.

4.3.2.4 Balcony and WC

The bioluminescence in the balcony and WC can be suitable for short-term usage. The bioluminescent photobioreactor was integrated on the wall near the living room door in the balcony. In Figure 4.10 and Figure 4.11, existing condition and bioluminescent light integrated condition of the balcony can be seen.

Figure 4.10. Existing lighting condition of the balcony in the day light.

Figure 4.11. The bioluminescent light in the balcony.

In WC, the bioluminescent light was applied between the toilet and sink to provide efficient lighting during the usage. Figure 4.12 displays existing condition of the WC. In Figure 4.13, the environment in the WC which is created by the bioluminescence after the integration can be seen.

Figure 4.12. Existing lighting condition of the WC with artificial light.

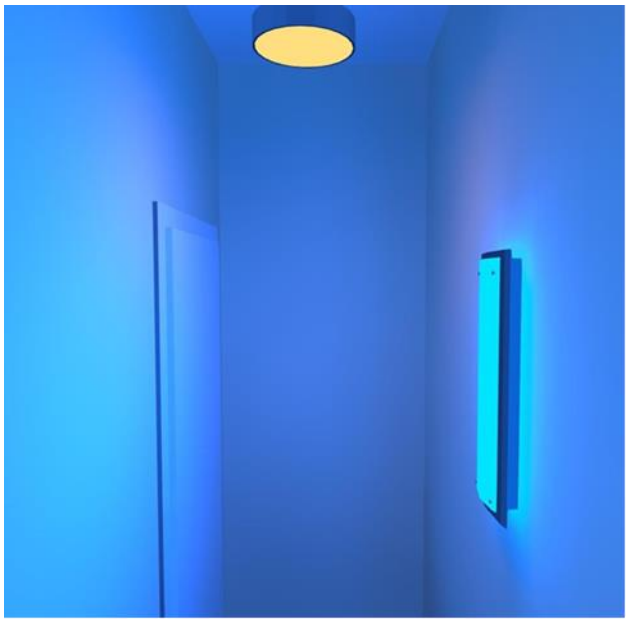


Figure 4.13. The bioluminescent light in the WC.

In this study, the technical and mechanical system of the bioluminescence photobioreactors, maintenance requirements, possible electricity usage for maintenance, cost-efficiency of the system and payback period were not included in the scope. During the dark period, algae needs constant stimulation for bioluminescence. Environmental factors such as temperature and oxygen supply should be under control inside the system. The algae species used in this study are photosynthetic and need natural sunlight for the survival. In the WC, there is no window to gather the natural sunlight. Integration of algae in the spaces without access to sunlight can be problematic. However, with the technical system allowing algae to circulate around the building like radiators of the heating system or with genetically modified bioluminescent species, this problem can be solved.

In the balcony, for transpassing purposes and short term usage, bioluminescence can be used. For other purposes which need longer usage of the area and higher luminosity levels, artificial lights can be operated. For this reason, the existing conventional light was not removed from the balcony.

Similar to the balcony, the bioluminescence can be utilized in the WC when occupants need to use the area for a short time period. Depending on the activities and the purpose of the usage of the area, the existing artificial light can be employed. Therefore, the conventional light in the WC was not displaced from the area.

The visual of the whole flat and the common circulation area after the bioluminescent light integration is shown in Figure 4.14.

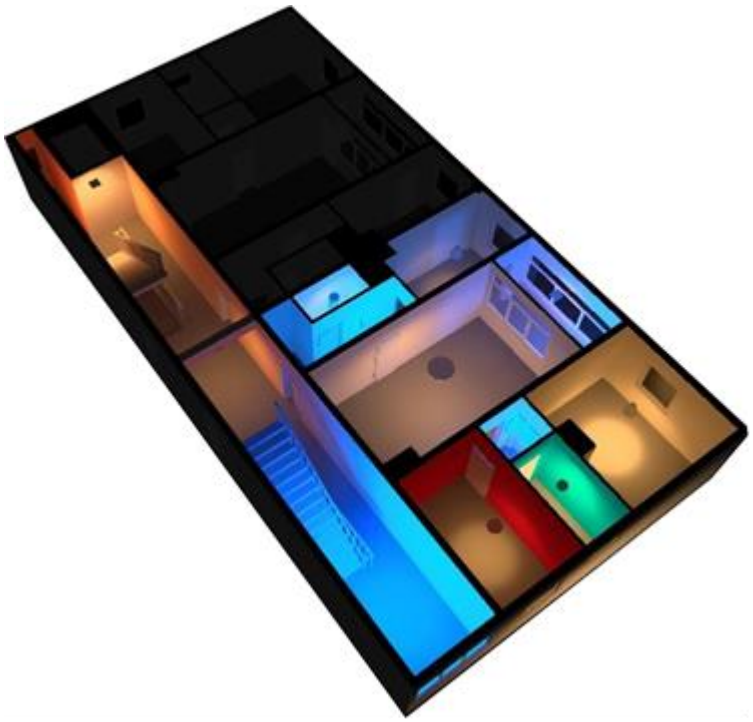


Figure 4.14. Render of the flat after bioluminescence integration.

The illumination values of the areas with the bioluminescent light integration were calculated in the simulation. In Table 4.14, the results of the lux amounts of spaces before and after the placement of bioluminescent photobioreactors were given with the target values in order to evaluate the bioluminescent light integration.

Table 4.14 Average illumination values of the areas with the bioluminescent light.

Spaces	Simulation results of the existing lighting situation (lux)	Simulation results with the bioluminescent light integration (lux)	Target Values (lux)
Circulation Area	38.4	127	100
Corridor	9.64	198	100
Entrance	89.4	156	100
Balcony	42.5	103	100
WC	40.8	208	200

Conducted lighting measurements showed that there were inefficient amounts of light in some of the rooms during the dark period of the day. The balcony, children's bedroom, circulation area, corridor, kitchen, entrance, living room and WC were below the target value with the lowest lumen amounts. For short time usage, guidance and transpassing purposes, bioluminescent algae were integrated only to the balcony, circulation area, corridor, entrance and WC. According to Table 4.14, minimum target values were achieved in the spaces with the bioluminescent light integration.

The results indicate that, depending on the placement of photobioreactors and the amount of algae, the target lux values can be achieved in the spaces with the help of bioluminescent light integration. These findings support the claim that bioluminescent light has the potential to be used in building interiors.

The existing artificial light was removed from the entrance, and the lighting of the area was proposed to be ensured only with bioluminescent light. These values in Table 4.14 display the results of the illumination after displacement of the artificial light and placement of the bioluminescent light. Simulations showed that, the integration of 2L of algae to the entrance provided a sufficient amount of light to reach the target value in the entrance without an artificial light. In addition to that, in the corridor area, there was no artificial light in existing situation, and with the 1L of algae integration, the target value was reached. These findings imply that integrating

algae into spaces as guidance light, where occupants use for a shorter time without an artificial light source, can be a practical application. Furthermore, bioluminescence can be used instead of conventional light sources in these spaces.

CHAPTER 5

CONCLUSION

Light has always been a curiosity builder for people. Being one of the inspiring phenomena in the nature, bioluminescence has been observed in many living creatures over the years. Microalgae and bioluminescent bacteria, the main subject of this research, are abundant organisms in the marine environment among bioluminescent creatures. These organisms have been used in several fields for years. From the food industry to energy production as biomass, microalgae have widespread of use. Likely, from criminology to environmental sciences as biosensors, bioluminescent bacteria found a place to be used. However, only recently have these organisms gained attention in the field of architecture.

In a new era with problems related to energy, alternative sources and sustainability, searching for new renewable sources becomes essential. In this study, the usability of bioluminescence was investigated, and the potential of bioluminescent light usage in building interiors was evaluated. The first objective was described as the identification of appropriate bioluminescent species for architectural usage from literature. In this scope, the bioluminescent algae *Pyrocystis fusiformis* was selected for the integration due to high luminous intensity. The second objective was determining the amount of light in building interiors with conventional light sources and with bioluminescent lighting to see the effect of bioluminescence. For this purpose, lighting measurements were conducted in each room of the selected flat with a lux meter. Later, simulations for the existing condition and bioluminescent light integrated conditions were done in the selected building flat. Based on simulations done by using lumen values of selected algae from previous work and the target illuminance values, the amount of bioluminescent algae that is needed for the lighting of the spaces were identified.The last objectives were simulating and visualizing the bioluminescent light in building interiors, and evaluating the possible

usage of bioluminescent light instead of conventional light sources in the building interiors. Filter tests and blue color experiments were conducted, and renders of the possible environment that is created by the bioluminescent light were demonstrated. Moreover, calculations of illuminance values after the bioluminescence integration done in simulations were discussed. According to the findings, the target lighting values can be reached in the interior spaces with the adjusted amount of algae. In addition, in the spaces where occupants' usage is short-time or where occupants are expected to use for passing to other spaces, it was seen that bioluminescent light could be integrated alone and used without any additional conventional light sources. The bioluminescent light in these spaces can provide guidance during the activity.

Recommendations for Future Research

This research illustrates the possible usage of bioluminescence in building interiors, but it also raises questions related to the requirements of the bioluminescent photobioreactor systems, maintenance issues, energy requirements, cost-efficiency and payback period of the system. Environmental factors such as sunlight and temperature should be considered in the mechanical system. Turbidity should be controlled in larger volumes. Because of being able to shine only a few seconds after stimuli, a system with a continuous flow may be required for algae in buildings, guaranteeing a constant brightness. The system may allow bioluminescent media to travel around the building like radiators and produce a more sustained glow. Moreover, when the bioluminescent system is used with biodiesel and electricity production in the buildings, the whole system will be more efficient. In addition, a small mechanism such as opening the door may be used for inducement of the mechanical stimulation that is needed for bioluminescence induction.

Due to the efficiency, LED lamps are one of the most commonly used ones in building interiors; however, materials that are used in LEDs have undesirable levels of toxicity and these light sources create light pollution like all other conventional light sources. With bioluminescence, toxicity and light pollution can be prevented.

Another factor that should be questioned is the color of the bioluminescent light. The original color of the bioluminescence of algae is in the blue spectrum. Blue light can affect the perception of materials with different colors. For different color options, filters can be adapted to the system or genetically engineered bacteria with different light spectrum can be used. Genetically engineered organisms with bioluminescence may also decrease the negative effects of environment on the living organisms. Future studies could address these questions and enrich the findings to better understand the implications of results.

This study evaluates how we can employ marine organisms with blue bioluminescent light in our houses. Previous studies mainly focused on the benefits of these species in other fields. In the architecture, it was proposed to be used in art installations, galleries, entrances, emergency exits, parks, arcades, facades as well as interior spaces. However, in this study, simulations of bioluminescent light and visualization of the possible environment created by bioluminescent light were shown to elaborate the previous studies further. To sum up, results indicate that bioluminescent light has the potential to be used in building interiors. It can be a new alternative light source in our houses in the future.

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APPENDICES

A. Filter Tests on Simulations

Table A.1 Blue color filter test with 3000 K° and the results.

Simulation with lowest lumen values (without algae)	**Incandescent standard halogen lamp**	Gathered data/ spaces	Circulation area	
			Elevator/Middle hall	
		Measurements	47/44	
		Simulation	44.7	
Algae integrated values (2x 5L)	**led 3000 k 075 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	121	
Algae integrated values (2x 5L)	**led 3000 k 118 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	189	
Algae integrated values (2x 5L)	**led 3000 k 119 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	58.2	
Algae integrated values (2x 5L)	**led 3000 k 132 filter**	Gathered data/ spaces	Circulation area	
			Elevator/Middle hall	
		Simulation	85.3	

Table A.1 Blue color filter test with 3000 K° and the results (continued).

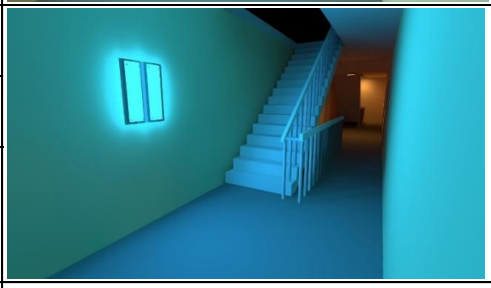
Algae integrated values (2x 5L)	**led 3000 k 165 filter**	Gathered data/ spaces	Circulation area Elevator/ Middle hall	
		Simulation	181	
Algae integrated values (2x 5L)	**led 3000 k 196 filter**	Gathered data/ spaces	Circulation area Elevator/Middle hall	
		Simulation	244	
Algae integrated values (2x 5L)	**led 3000 k 068 filter**	Gathered data/ spaces	Circulation area Elevator/ Middle hall	
		Simulation	107	
Algae integrated values (2x 5L)	**led 3000 k 069 filter**	Gathered data/ spaces	Circulation area Elevator/Middle hall	
		Simulation	133	
Algae integrated values (2x 5L)	**led 3000 k 141 filter**	Gathered data/ spaces	Circulation area Elevator/ Middle hall	
		Simulation	174	

Table A.1 Blue color filter test with 3000 K° and the results (continued).

Algae integrated values (2x 5L)	**led 3000 k 065 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	256	
Algae integrated values (2x 5L)	**led 3000 k 067 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	207	
Algae integrated values (2x 5L)	**led 3000 k 140 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	372	
Algae integrated values (2x 5L)	**led 3000 k 161 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	225	

Table A.2 Blue color filter test with 4000 K° and the results.

Algae integrated values (2x 5L)	**led 4000 k 075 filter**	Gathered data/ spaces	Circulation area Elevator/ Middle hall	
		Simulation	127	
Algae integrated values (2x 5L)	**led 4000 k 118 filter**	Gathered data/ spaces	Circulation area Elevator/ Middle hall	
		Simulation	198	
Algae integrated values (2x 5L)	**led 4000 k 119 filter**	Gathered data/ spaces	Circulation area Elevator/ Middle hall	
		Simulation	61	
Algae integrated values (2x 5L)	**led 4000 k 132 filter**	Gathered data/ spaces	Circulation area Elevator/ Middle hall	
		Simulation	90.3	
Algae integrated values (2x 5L)	**led 4000 k 165 filter**	Gathered data/ spaces	Circulation area Elevator/ Middle hall	
		Simulation	189	

Table A.2 Blue color filter test with 4000 K° and the results (continued).

Algae integrated values (2x 5L)	**led 4000 k 196 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	251	
Algae integrated values (2x 5L)	**led 4000 k 068 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	113	
Algae integrated values (2x 5L)	**led 4000 k 069 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	139	
Algae integrated values (2x 5L)	**led 4000 k 141 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	183	
Algae integrated values (2x 5L)	**led 4000 k 065 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	263	

Table A.2 Blue color filter test with 4000 K° and the results (continued).

Algae integrated values (2x 5L)	**led 4000 k 067 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	214	
Algae integrated values (2x 5L)	**led 4000 k 140 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	381	
Algae integrated values (2x 5L)	**led 4000 k 161 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	232	

Table A.3 Blue color filter test with 5500 K° and the results.

Algae integrated values (2x 5L)	**led 5500 k 075 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	143	
Algae integrated values (2x 5L)	**led 5500 k 118 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	224	
Algae integrated values (2x 5L)	**led 5500 k 119 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	68.4	
Algae integrated values (2x 5L)	**led 5500 k 132 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	105	
Algae integrated values (2x 5L)	**led 5500 k 165 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	212	

Table A.3 Blue color filter test with 5500 K° and the results (continued).

Algae integrated values (2x 5L)	**led 5500 k 196 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	270	
Algae integrated values (2x 5L)	**led 5500 k 068 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	130	
Algae integrated values (2x 5L)	**led 5500 k 069 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	160	
Algae integrated values (2x 5L)	**led 5500 k 141 filter**	Gathered data/ spaces	Circulation area	
			Elevator/M iddle hall	
		Simulation	212	
Algae integrated values (2x 5L)	**led 5500 k 065 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	282	

Table A.3 Blue color filter test with 5500 K° and the results (continued).

Algae integrated values (2x 5L)	**led 5500 k 067 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	235	
Algae integrated values (2x 5L)	**led 5500 k 140 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	401	
Algae integrated values (2x 5L)	**led 5500 k 161 filter**	Gathered data/ spaces	Circulation area	
			Elevator/ Middle hall	
		Simulation	251	

B. Filters Used from DIALux Catalogue for Filter Tests

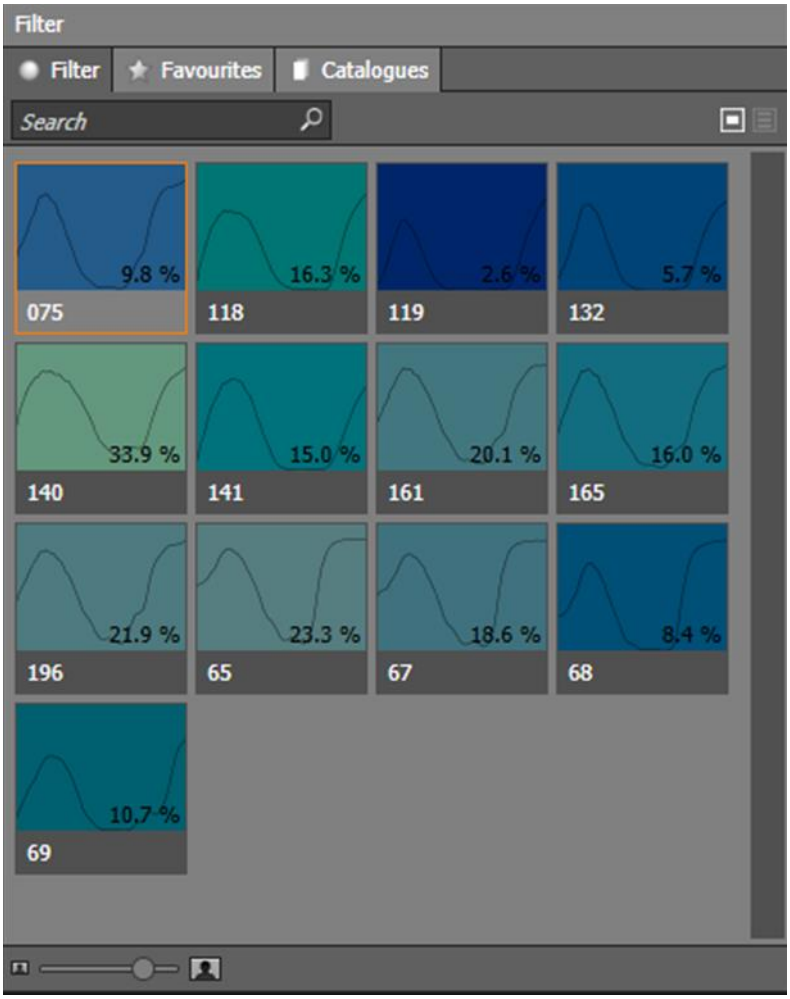


Figure A.1. Blue filters chosen from the DIALux filter catalogue.