Bioluminescent algae and possible implications in architectural design

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ABSTRACT: Today, most common light sources derive their energy from the burning of fossil fuels. This both causes climate change and the depletion of nonrenewable resources. In 2010, 67.6% of global electricity production originated from fossil fuels. Of the remaining sources, only 3% were renewable. As the impact of carbon emissions is global, their reduction is the responsibility of all. Bioluminescence has not garnered much attention as an energy source. This energy, produced from biological organisms that produce light by a chemical reaction, does not produce heat as a byproduct unlike most other energy sources, yet generates enough light to be detected. Algae are a potentially good source for bioluminescence and it remains virtually un-pursued in this field. The use of bioluminescent algae in both the urban and architectural fields through photo-bioreactors is an option that we intend to pursue by developing performance measurement systems. They could be an effective light source for practical applications of elegant lightning solutions at significantly less cost to the planet than current methods. This paper discusses the results obtained by previous experiments in the biological field. It intends to establish a comparison with ideal lighting conditions for different uses in space.
Keywords: Bioluminescence; energy; light; algae; design

INTRODUCTION

Microalgae have the potential to impact a wide extent of products. These can range from being used as a source of energy production to creating biological sensors for water pollution. One of its greatest qualities is its bioluminescence; its ability to generate light. Specifically, bioluminescence is any type of light emitted by a living organism caused by a chemical reaction between enzymes and oxygen. It requires the presence of a protein called luciferin, an enzyme catalyst called luciferase, molecular oxygen and ATP (adenosine triphosphate), a substance capable of generating the energy required for the reaction. Oxygen oxidizes the luciferin, luciferase accelerates the reaction, and ATP provides the energy for the transformation to a new substance (luciferin oxidized), releasing the excess energy as light without generating heat. Endurance, intensity, frequency, and color vary depending on the species involved in the reaction.

Phytoplankton is the focus of this study due to the strength of the brightness emitted by its reaction. We presume that the energy generated by this kind of algae can provide adequate levels of lighting in public and residential spaces. Additionally, with the social assimilation of the aesthetics of algae, the cultivation of this vegetation can be utilized in the creation of green areas and as an integral system for urban landscaping, reducing light pollution and creating a positive impact in neighborhoods saturated with population and/or contamination. Since most existing research on the subject does not have an architectural focus, a study such as the one proposed below would be desirable.

LEVEL OF BIOLUMINESCENCE IN MICROALGAE

Plankton and algae

Plankton is a set of organisms that float in water and are carried away by water flows in rivers and at sea. Zooplankton and phytoplankton are directly or indirectly the primary food source for almost all marine organisms. Phytoplankton is composed of siliceous skeletons and celled groups, such as diatoms, dinoflagellates and coccolithophores. Their population in the water varies depending on season, temperature, and minerals [26].

Plankton in many cases has been associated with an extensive display of bright bioluminescence on the water surface [12]. Also known as milky seas, this display is a result of a high concentration of bioluminescent organisms, distinguishable even from satellite imagery [10]. The study of bioluminescence in plankton has served to identify the diversity and variability of

organisms, revealing structure and trophic interaction between different communities [19].

The study would focus on one of these communities, the dinoflagellates, whose light is associated with "bright sparks." There are at least 18 genera which produce light [2], among which are *gonyaulax* (a synonym for *lingulodinium*), *noctiluca*, *protoperidinium* and *pyrocystis* [10]. In nature, large quantities of these species can be found at the surface levels due to their photo-autotrophic nature, making them difficult to find at great depths [23]. They can be cultured in a laboratory with relative ease provided they have the correct media. It must be noted however that some of these species are dangerous because they serve as an environmental control and bloom with certain types of bacteria and pollutants [5]. Depending on the strain, they can last up to 20 years although it has been shown that over time they lose their photosynthetic capacity [25].

In dinoflagellates, bioluminescence is due to circadian rhythm. It presents its greatest intensity during the hours of darkness [3]. Analyzing its glow in nature requires the consideration of various factors such as the noise produced by other plant and animal bioluminescent species and the location of these species as their relative closeness to coastal areas affects their intensity [23]. In the case of culturing laboratory single species, the brightness is dependent on the type of cell and the kind of stimulus made [6].

Selected algal strains

An analysis was made of different dinoflagellates species that can produce light. Geographical and natural conditions also influences fundamentally in the samples [19] therefore there were considered algae species dwelling within the Mexican territory and its vicinity. The ones described below, can be found in California and the Sea of Cortez in Baja California Mexico.

Clasification	Description	
Genera	Image	Culture
Gymnodinium		Marine / fresh water
Dissodinium/ Pyrocystis		Marine
Ceratium		Marine
Ceratocorys		Marine
Gonyaulax		Marine
Pyrodinium		Marine

Table 1. Studied algal strains

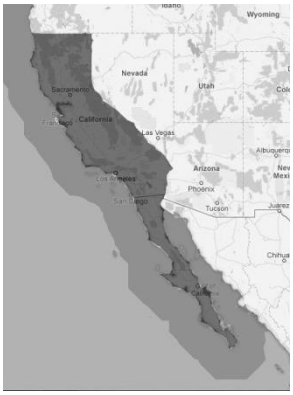

Figure 1. Geographical area of studied algal species.

EXPERIMENTAL PROCEDURE

General Considerations

Measuring light in microalgae is a delicate process, not only because the nature of the culture strains but also for the management of this type of organisms. Some can be toxic and their marine environment makes them very sensitive to all kind of stimuli.

The equipment used for measurements is highly accurate and most of the times built specifically for this purposes. Species differences, the method by which the stimulus is made, the frequency and intensity at which they are excited, the amount of stress they can bare before genetic damage and decrease in the resilience of algae, are some of the inputs should be taken into account.

The study case is bounded to the characteristics of light emission by the studied cells. Measurements are compared in terms of features, usability and light outputs to determine its possible implication in architectural design. Revealed information may result in future research to develop devices to achieve controlled lighting in spaces. It's required to substantiate in previously obtained values in the biological field, thereby is hoped to obtain accurate understanding of the light emitted by algae and the activities that could develop properly with this kind of lighting. There were considered different schemes and values to analyze the results in an average production of bioluminescence, in that way peak values were avoided, ensuring an outcome as close to possible reality.

Development

In natural environment, the highest concentrations of cells are distributed according to the depth, and surround to the coast. Measurements taken at bays have shown a higher incidence of cells on the continental shelf than in the abyssal terrace [19]. Due to their phototrophic nature large amounts of these species lives on the surface of the water, being difficult to find them at great depths [23]. Such readings in the natural environment are taken on board vehicles equipped with readers' navigation probes and portable laboratories. The concentrations of cells in taken samples will be smaller; in most cases will occur in combination with other species. In contrast, laboratory studies have a much higher concentration of individuals due to controlled environment reproduction, resulting in a higher light intensity in each sample.

There were analyzed the results obtained for the genera *Ceratium*, *Ceratocorys*, *Gymnodinium*, *Lingulodinium* (*Gonyaulax*) *Pyrocystis* and *Pyrodinium*. All of them are eukaryotic unicellular dinoflagellates capable of present bioluminescence. For field measures it was taken into account the results by; Lapota & Losee [12] Lapota [14] and Moline [19]. For laboratory tests, results reported by; Biggley [3] Cussatlegras & Le Gal [6], and Latz [15].

Analyzed values

Field lectures showed once the sample is stimulated luminescence peak lasts less than seconds with a fixed term and decays in a hurry to get back to the dark [12].

Lab studies have analyzed bioluminescent responsiveness linked to time exposure periods of both light and darkness [7] [15], the cells were mechanically excited both times and with equal intensity they shine less time when cells were exposed to light than when they were in the dark phase [3]. It has been proven that algae may have a stronger bioluminescence with turbulence stimuli at a single speed [6]. The stimulation by which each cell type was excited speaks about cell performance. Fact that can be useful in the development of any possible device as posed in this study.

This paper has reviewed and analyzed the reported results of bioluminescent algae in both cultivated systems and natural environments, focusing on the number of photons emitted by each kind of cell. To provide a range of values more accurately, it is necessary standardize in mean values the collected results.

Nomenclature	cell amount	photons	flash	λ
Species / unit	1 mL	c•s	ms	nm
Ceratium	7.54	1.75E+09	232	475
Ceratocorys	15.00	2.59E+09	184	475
Gymnodinium	0.35	7.00E+07		475
Lingulodinium	5684.00	2.94E+09	125	478
Pyrocystis	1008.60	1.30E+10	155	477
Pyrodinuim	4233.00	3.35E+08		475

Table 2 Summary of cell type and amount of emitted photons

Photons vs lumens

In biology, the amount of light emitted by an organism is measured in photons, making the quantity of emitted photons by any light source directly proportional to the amount of generated energy. In architectural and lighting international measurement systems, the base unit to measure light output is the lumen (lm), referring to the "luminous flux" of total visible light emitted by a source at any angle. When accounting for the incidental luminous flux at a given space or surface, it is transformed into a measurement called a lux which represents the illuminance of the lighting source. Most lighting standards utilize the lux or lumen depending on the planned activity. Other measurements derive from lumens such as candles per meter and watts (when measuring energy efficiency).

Because of these differences in measurement standards, in order to interpret the light output of the algae, it is necessary to perform a series of conversions to obtain the amount of energy produced in photons per cell per second in lumens and then to create a comparison with the lighting requirements of a space. In other words, we need to translate the photon flow into light output measurements.

Conversions

As an example, there were converted results of one cell type. A particular kind of algae which is the most efficient in terms of light intensity [3] and recovery of the cell itself [15]. There were taken into consideration, the number of cells contained in 1 mL of the sample and the number of photons emitted [6], the wavelength and brightness of the sample [14].

Cell species	cells/mL	Photons / cell	Flash length	λ
pyrocystis	325	1.10E+08	100 ms	475 nm

Table 3. Data for unit conversion

It was used the formula:

$$1\ \text{lm} = \text{cd} \bullet \text{sr} = \text{lx} \bullet \text{m}^2$$

Planck's constant was taken as reference to calculate the photon energy.

$$E = \frac{hc}{\lambda}$$

$$E = \frac{6.626 \times 10^{-34} J \cdot s\ (2.998 \times \frac{10^8 m}{s})}{475 \times 10^{-9}} = \frac{1.99 \times 10^{-25} J \cdot m}{475 \times 10^9}$$

$$E = 4.18 \times 10^{-19} J$$

Where:
E = photon energy
h =Planck constant
c = light speed
λ = wavelength
J = joules

Then:

$$1.10 \times 10^8 (325) = 3.58 \times 10^{10} \frac{photons}{c \cdot s}$$

$$3.58 \times 10^{10} \frac{photons}{c \cdot s} \times 4.18 \times 10^{-19}\ \text{J} = 1.49 \times 10^{-8} \frac{\text{J}}{c \cdot s}$$

The candela is the luminous intensity in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 Watt per steradian (National Institute of Standards and Technology, 2010). Therefore:

$$1cd = \frac{1}{683} W = \frac{1}{683} \frac{J}{s} = 1.46 \times 10^{-3} \frac{J}{s}$$

$$X = \frac{1.49 \times 10^{-8} \frac{J}{c \cdot s}}{1.46 \times 10^{-3} \frac{J}{s}} = 1.02 \times 10^{-5} \frac{J \cdot s}{J \cdot c \cdot s} = 1.02 \times 10^{-5} \frac{1}{c}$$

Where:
J = joule
c =cell amount
s = second
W = watts
cd = candela

Then:

$$\text{X} = 1.02 \times 10^{-5} \frac{cd \cdot sr}{c} = 1.02 \times 10^{-5} \frac{lm}{c}$$

It was assumed, we were exposed to algae brightness for an hour, therefore:

$$1.02 \times 10^{-5} \frac{\text{lm}}{c} (3600) = 0.04 \frac{lm}{c}$$

The amount of energy produced in an hour by sample cells contained in one milliliter equals 0.04 lumens. This represents the potential amount of light emitted by the source. An increase in milliliters will consequently result in a higher quantity of lumens For analysis purposes the procedure described above was repeated for each of the mean values obtained from sample values.

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)

Table 4. Milliliter ratio and equivalent luminous flux

The continuous excitation of the same cells produces individuals' exhaustion. Since light emitted by algae occurs only during the first few seconds of stimulation [14] it's suggested a continuous water flow which would guarantee a continuous brightness. In the successful deployment of a device there should be considered most meticulously flow conditions, in order to get the best benefit from them

DISCUSSION AND RESULTS

Light parameters and human vision

Sight operation and color disappearance make the eye capable to see at night below 1 lux luminance. Emitted wavelength is 470-490 nm. [14], it corresponds to blue spectrum. Although analyzed species present in small quantities low luminous flux, because color perception favors in the dark blue tones [8], the spectrum emitted by these organisms is more easily distinguished at night. This coincides with the period of greater intensity in the cells brightness. Therefore, use of produced bioluminescence is bounded by schedule.

Is presumed the best job for the obtained light output could be public lighting. Algae light may be used where no point illumination is needed and could be decorative and functional, both indoor and outdoor. Such device might be the basis for staging microalgae in built spaces and urban vegetated areas. They would provide light during night hours offering energy save and reduction in light pollution.

Through inverse square law were established illuminances projected on a surface at different distances.

Sample size	Mean lumen amount	Distance (meters) 0.5	1	1.5	2	2.5	3
3 mL	16	64	16	7	4	2.6	1.8
100 mL	534	2136	534	237	133	85	59
250 mL	1335	5340	1335	593	334	214	148
500 mL	2670	10679	2670	1187	667	427	297
1 L	5340	21358	5340	2373	1335	854	593
5 L	26698	106791	26698	11866	6674	4272	2966
10 L	53396	213583	53396	23731	13349	8543	5933
liquid	lumens			lux			

Table 5. Lumen proportion and lux

Because light emitted by algae is diffuse, it becomes less efficient at heights over 3 meters above floor level, since all the illumination would disperse before reaching the object or site to be illuminated. Meeting the minimum required distance for the lighting source can also lead to complications. That would result in impractical design due to large amounts of suspended liquid.

Interpretation of luminous flux was referenced to lighting standards [1] [22] [21] [18] [4] [11]. Specific requirement for the proposed use and some examples are shown immediately.

EXTERIORS		
Street in a residential area	4 - 7	Lux
Important commercial avenue	15 - 20	Lux
Plazas	10 - 20	Lux
Parking lots	50	Lux

Table 6. Outdoor illuminance

In public lighting, roads and walk ways are classified for use according different needs, so that, not only fulfills its function to illuminate, but also provide pleasant environments. We suggest that microalgae bioluminescence can be used as orientation luminaires. As the name implies, are defined through the guiding role. It can be accomplished by general lighting fixtures, wall mounted luminaires or signaling luminaires, these act as local guiding lights. They may be employed in facades, entrance areas, arcades, galleries, ground roads illumination, streets and squares, steps or prohibited areas, entrances, emergency exits and parks.

Comparison of the quality and light color emitted by microalgae, over existing light sources, yield performance of the luminous flux, with advantages and disadvantages. It was proven that algae have cold color temperature, their illuminance is high, and present high efficiency since light output does not generate any heat. Their lifetime can be prolonged as long as desired provided the correct habitat, being that they are living organism. The weak points are the cost of maintenance a system like this could pose, also the possible effect of small changes in their habitat could affect algae and

light output finally its use could be both seasonal and local.

Its inferred algae color rendering index (CRI) will be similar to that of a gas. Light sources are many and present bioluminescence in short time and vary depending on cell type. Light emission therefore will not be continuous; even if because of the flow would appear otherwise. The observed colors levied under this type of lighting will be distorted according to the tones that emit and absorb. For proper performance of designed luminaires, light uses should contemplate shape and texture in close objects. This does not represent a disadvantage, since most of the lamps employed to the proposed use have the same feature.

Lamps	Spotlight shapes	Relative spectral distribution	Color temperature	Efficiency	Lifetime (hours)
Incandescent lamps			Warm	Low 7-14 lm/w	1000
Tungsten halogen lamps			Warm	10-17 lm/w	2000
Fluorescent and compact fluorescent lamps			Warm white	High 30-70 lm/w	5000 – 10000
			Daylight white		
			Neutral white		
LEDs lamps			RGB	High 30-100 lm/w	100000
			Warm white conversion		
Dinoflagellates			Cold	High 100 lm - no watts	Everlasting

Table 7. Algae comparison of luminous flux, color temperature and luminous efficiency with different light sources.

CONCLUSIONS

Dinoflagellates are sensitive organisms whose excitement and illumination time depends on many different circumstances. Analyzed values reflect only part of their natural instinct and data obtained in various studies over several decades. Although they represent a well-known domain, in anyway involve easiness in the deployment of a system that could provide illumination such as the one proposed in the study.

It has been found in field samples that luminescence not only depends on the dinoflagellates species being analyzed, but also on the location where it can be met [13]. Factors such as depth at which the sample was performed also influences; these species exist in a much higher proportion over water surface than in shots made 5 m. deep. There are strong differences in samples readings according to the season of the year when the survey is made [19]. The size of a bioluminescent body can be misleading, in the amount of light produced. Although it might seem that larger species, such as certain types of crustaceans, emit greater amounts of light, in a stable condition of any ecosystem will be a much smaller number of these individuals. Planktonic dinoflagellates communities are responsible of 70 to 90% bioluminescence captured at sea. Saturation of these has direct impact on the quantity and quality of obtained light. It must be seen that the best cell growth stage for better results of higher brightness is the youthful and adult stage [13]. Responsiveness to flow conditions corresponds to the shape and physiology of the cell itself [15]. The extended bioluminescence in time series can be obtained in constant flow conditions [15].

It possible implication with architecture might work in coastal cities on par with control and toxicity testing, marine bioluminescent dinoflagellates provide a fast and sensitive assessment of current environmental conditions [14]. The proximity of its use with the natural habitat of these organisms could imply a complete action cycle, since it would help to reduce maintenance and performance costs. It is intended that more research and development, would lead to combined uses, both to illuminate and as water treatment, food generation, biofuels or other.

Perhaps its most significant potential is the artistic one: building decoration, land art, piers and marina illumination, reef delimitation and ephemeral art installations could embody this technology. This also would manage to attractively incorporate in urban space, new forms of awareness about nature and environment.

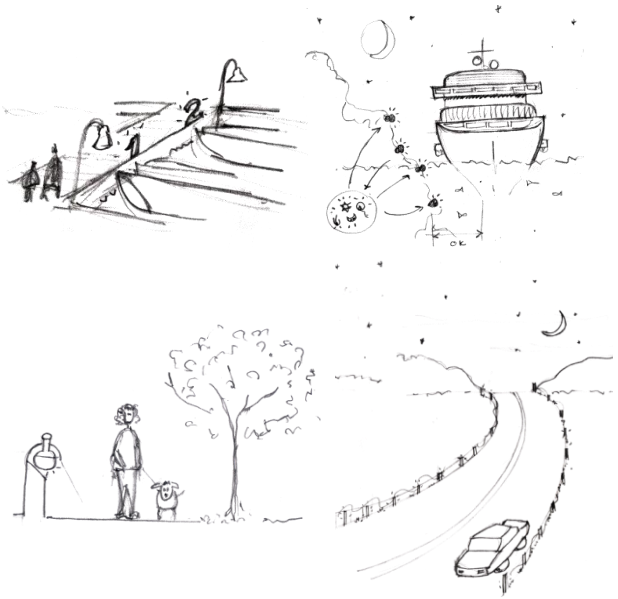

Figure 2. Potential uses of algae

Results of this research suggest algae implications on architectural design. It is intended this study serve as basis to other developers in different areas in order to achieve success. Affordable, correct, and timely development of this technology still depends on many factors, nonetheless is an option worth pursuing by the benefits it offers.

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