Journal of Animal and Veterinary Advances 7 (7): 841-846, 2008
ISSN: 1680-5593

Bioluminescence in Aquatic Organisms

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Abstract: Bioluminescence is a light production phenomena performed by means of chemical reactions or cellular secretion existing in the cells of living organisms or in the cells and organs of the symbiotic organisms which live together with them. In this process, at least two chemicals, luciferin and luciferase, are required. Bioluminescence can be seen in a wide range of groups of aquatic organisms such as phytoplankton, zooplankton, annelids, molluscs, ctenophores, shrimps and fishes. Bioluminescence in aquatic organisms, just like in terrestrial bioluminescent organisms, provides hiding and protection, attraction of prey or communication. The most common example of bioluminescence is light production by *Noctiluca miliaris* called as "phosphorescence in the sea". Because it is thought that light-producing organisms (bioluminescent) may be used or cultured for many aims in the future, formation of bioluminescence, its usage by aquatic organisms and its effects will be tried to explain in this review.

Key words: Bioluminescence, aquatic bioluminescent organisms, bioluminescence effects, luciferin, luciferase

INTRODUCTION

Bioluminescence (biological light) is in brief a production of light performed by some aquatic and terrestrial organisms. Bioluminescence occurs in organisms living in the surface layer (euphotic zone) or much deeper layers (dysphotic zone, aphotic zone) of the seas and the oceans. Though it could be observed in the terrestrial organisms (glowworms, some fungus, some earthworms etc.), bioluminescence could also be observed in a great variety of aquatic organisms, ranging from bacterium and plankton to many invertebrate and vertebrate animals. It is now known that more than 90% of aquatic organisms have the peculiarity of bioluminescence. Expansion of the single cellular marine organisms (especially *Noctiluca* sp. Dinoflagellate), which raised to surface of seas and oceans in night time for nutrition, is one of the main reasons of biological shining which is also known as "phosphorescence in the seas" (Herring, 1987; Tüzün *et al*., 1992). And bioluminescence is the main source of light for deep waters.

Though, it has been generally stated that the bioluminescence doesn't occur in the organisms which inhabit the fresh waters, Meyer-Rochow and Moore (1988) reported an only light-producing freshwater snail (*Latia neritoides*) in the world. Yet, it couldn't be determined definitely why bioluminescence does occur so rare in the fresh waters (Harvey, 1952).

Bioluminescence differs from fluorescence and phosphorescence. Light absorbed from a light source is reflected as a different radiation with various wavelengths in fluorescence and phosphorescence events, whereas in bioluminescence, energy required for light production is produced within the cell by a chemical reaction (Gitelson and Levin, 1999). Because very little heat is produced during bioluminescence, the light formed in this process is named as "cold light" (Hastings, 1983, 1996; George and Philips, 1997).

Bioluminescence could be seen in spectacular forms with the vibrant and spiral diffusions of parallel lines on the surface stretching towards horizon.

Especially, the light formed by highly organized animals is produced and reflected directly by their complex light organs which have many light cells called photophore, a reflector and a lens collecting lights in bundles. Some aquatic organisms not producing light live in symbiosis with bioluminescent bacteria. These non-bioluminescent organisms have small purses where the sparkling bacteria inhabit; therefore they indirectly produce light by means of these bacteria. When they don't want to produce light, they envelop the purses with membranous valves (Tüzün *et al*., 1992).

While, some aquatic organisms give off continuous light, many others give off lights within a rate ranging from 0.1-10 sec. Some dinoflagellates make a continuous response to short-time stimulation. Sparkling is generally

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controlled by neural system in multicellular organisms. In some kind of fish, bioluminescence is controlled by sympathetic nervous system, a part of nervous system acting according to sense. In some single-celled organisms, bioluminescence could be started by applying small forces on the cellular surface (Wilson and Hastings, 1998).

It is observed that the main reason why an organism produces light, however it is not absolutely clear, is related to vital functions like reproduction, nourishment, defense and communication (Hastings, 1983; Herring, 1987).

It was stated that some bioluminescent bacteria were grown in culture conditions and bioluminescent marine bacteria had potential biotechnological applications (Herring, 2002; Wegrzyn and Czyz, 2002). This statement makes it easier to think that culturing of many bioluminescent aquatic organisms and use of them in biotechnological applications may be widely under attention in the future.

In this study, the aim is to explain bioluminescence, its formation by giving the examples of known and important aquatic bioluminescent organisms and by implying the effects of bioluminescence. So, it is expected that this review will contribute to possible use or culture activities of aquatic bioluminescent organisms in the future.

FORMATION OF BIOLUMINESCENCE

There are several essentials of formation of all bioluminescence reactions. The first of these essentials is the existence of oxygen in the ambient.

The second is the necessity of luciferin protein and luciferase enzyme. Luciferin and luciferase exist in the form of photoprotein in many aquatic organisms. And the structures bearing photoproteins are either photocytes or photophores (Reichl *et al*., 2000; Sukatar and Karaboz, 2001).

In addition, the existence of inorganic ions (especially calcium (Ca^{++}) (Sukatar and Karaboz, 2001), magnesium (Mg^{++}) and and adenosine triphosphate (ATP) in the ambient have roles in the process (Tanyolaç and Tanyolaç, 1985).

Luciferin is the main substrate for reaction (Fig. 1). It forms luciferin ATP by reacting with ATP in an oxygenic ambient. After that, luciferin ATP forms oxiluciferin and light by being oxidized with the aid of luciferase in the ambient in which ions exist (Tanyolaç and Tanyolaç, 1985).

Luciferin is either produced by organism or taken from environment by means of nutrients for its vital activities.

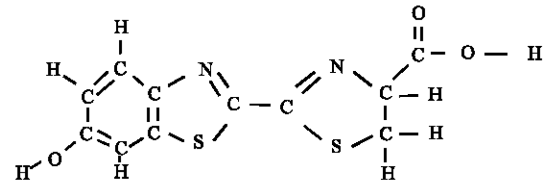


Fig. 1: Chemical structure of luciferine (Brasier *et al*., 1989)

Production of light from photoproteins in Coelenterata generally occurs after the addition of Calcium ion (Ca^{++}) into the system. As for the dinoflagellates, bioluminescence occurs in organelles (known as “scintillons”) that are situated within the vacuoles in cell’s cytoplasm (Hastings, 1983, 1996; George and Philips, 1997).

Types of luciferin: Tough there are hundreds of types of aquatic bioluminescent organisms, there are only a few types of luciferin which are the main substance for light production.
Five types of luciferin are known:

Bacterial luciferin: Reduced riboflavin phosphate ($FMNH_2$). It could be seen in bacteria, some fishes and squids.

Dinoflagellat luciferin: Since it shows a structure similar to chlorophyll, it is thought to be derived from chlorophyll. It exists in dinoflagellates and krills.

Vargulin luciferin: This type is found in Ostracodes and *Vargula* (Poricthys).

Coelenterazine: This is the most common type of luciferin. It could be seen in many phylums (Radiolaria; Ctenophora; Cnidaria; Mollusca (Cephalopoda); Arthropoda (Copepoda and some Decapoda (some shrimps); Chaetognata; Chordata (some fishes)).

Glowworm luciferin: This type of luciferin requires ATP for reactions. It is found in glowworms (Sukatar and Karaboz, 2001; Brasier *et al*., 1989; Jones *et al*., 1999).

COLORS OF BIOLUMINESCENCE

Color of light given by aquatic organisms is generally blue. One reason for that, blue light has the shortest wavelength and beams the biggest quantity of energy, so that it can reach long distances in the sea. Besides, it is the blue light (wavelength of 450-490 nm) to which marine organisms are most sensible.

There are also some aquatic organisms giving off green, yellow, orange and, as in genuses *Malacosteus* and *Aristostomias*, red light apart from blue. Yet, it is known that some marine organisms give off lights in 2 different colors (Herring, 1985; Nealson and Hastings, 1992).

Tough, red and green lights enable the organisms to recognize long distances, these lights also make them visible.

Organisms projecting long-wave red light have relatively shorter sights, but their locations cannot be recognized from distant points. This feature provides them with complete secrecy while observing their hunts. These organisms use red light for observation and blue-green light to warn others (Campbell and Herring, 1987).

To give off light, these organisms initially use their lighting organs named as photopore. At the beginning, light is not red (its wavelength is short). After produced, this light is partly absorbed in photopore. As a result, color of light turns into red (Herring, 1985; Nealson and Hastings, 1992).

BIOLUMINESCENT ORGANISMS

Bioluminescence occurs in many different aquatic organisms like bacteria, squids and many other organism groups. For instance, it was determined that when the lighted worms existing around Bermuda, a kind of annelid, gathered close to water surface once a year for reproduction, they caused sea to sparkle (Tüzün *et al*., 1992).

The groups represented in Table 1 are bioluminescent organisms in respect to at least one species, though not fully (Nealson and Hastings, 1992). The most well-known samples which exhibit bioluminescent peculiarity are given under this title.

Table 1: Groups of bioluminescent aquatic organisms

1.Bacteria	10.Anthozoan	19. Copepoda
2.Fungus	11.Ctenophora	20.Euphausidae
3.Plankton	12.Mollusca	21.Chaetognatae
4.Annelid	13.Nudibranchia	22.Echinodermata
5.Hemichordata	14.Octopoda	23.Asteroidea
6.Radiolaria	15.Cephalopoda	24.Ophiuroidea
7.Cnidaria	16.Tunicata	25.Holotharidea
8.Scyphozoa	17.Pycnogonidler	26.Ostracoda
9.Hydrozoa	18.Crustacea	27. Pisces

Plankton

***Noctiluca miliaris* (Noctilucaceae):** Zooplankton named as *Noctiluca miliaris* is a large flagellate that lives in sea (Fig. 2a). Bioluminescence occurs directly in this species (Anonymous, 2006a).

Cnidaria (Coelenterata)

Jellyfish producing light: Many of the jellyfish are bioluminescent (Anonymous, 2006 b). There are cells like suture over their dorsal that can produce light (Fig. 2b and c). Species have different and strange peculiarities within themselves. For instance, on being touched, red jellyfish shines and could leave sparkling pieces into sea. This is a method used to bewilder enemies (Ganeri, 1999).

Mollusks (Mollusca)

Squids: The short-tailed squids *Euprymna scolopes* (Sepiolidae) (Fig. 2d) and the bacteria producing light lead a symbiotic life. These bacteria live in a dent embedded in the mantle of squids. This kind of squid passes its days hiding under sands in the shallow waters. When it comes out for hunting in nighttime, the bacteria begin to sparkle. Thus it enables the animal not to be realized among night-light (Hamilton, 1999).

As for the squids projecting light (Fig. 2e), they produce blue-white light in their cells chemically. Their bodies and tentacles are covered with organs resembling jewels. The peculiarity of this squid is that it can adjust the color, density and the angle of the light in accordance with the surroundings so as to be camouflaged. It is thought that female squids produce light either to allure males or to protect themselves. They can make themselves invisible to the eyes of their enemies by making adjustment in accordance with the light coming from above (Ganeri, 1999).

Crustaceans (Crustacea)

Ostracodes: Ostracodes the biggest of which is 30 mm are crustaceous organisms and some of its species live in seas. Some of them produce light (Fig. 2f). Male individuals of some species leave a trace consisting of luminous dots by secreting sparkling items from the glands of their upper lips in night, so as to allure female individuals. As a consequence of these traces, thousands of lights sparkling are seen in the seas where Ostracodes inhabit (Batten, 2001).

Spiny Skins (Echinodermata)

Starfish (asteroidae), sea urchins (echinoidea) and feathered stars (crinoidea): These organisms produce their own light to protect themselves against their enemies. They have luminous arms or spines, so they could produce light clouds when attacked.

Starfish inhabit approximately 1000 m below the seas. They give off green-blue light through the distal parts of their arms. Their sparkling warning is to notify that they have bad tastes. Yet another kind of starfish begins to sparkle and throw one of its arms towards enemies to keep

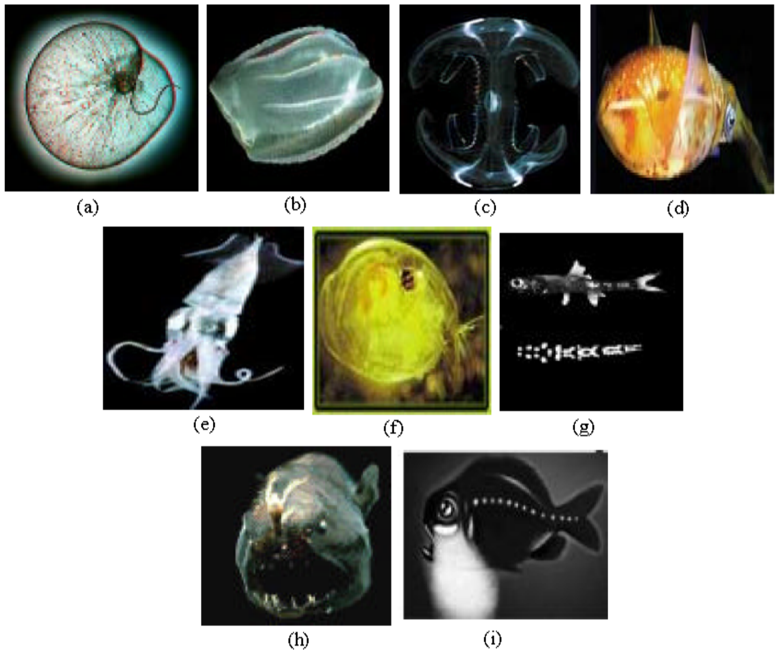


Fig. 2: Bioluminescent Aquatic Organisms (a: *Noctiluca miliaris* (Harvey, 1952); b and c: jellyfish (Ganeri, 1999); d: *Euprymna scolopes* (Ganeri, 1999); e: Lightened-squid (Ganeri, 1999); f: Ostracode (Batten, 2001); g: *Ceratoscopelus maderensis* (Johnsen *et al.*, 2004; h: *Lophius piscatorius* (Widder, 2001); i: *Photoblepharon palpebratus* (Anonymous, 2006c)

them away when attacked. This is an important defense tactic used by starfish. Arm thrown by starfish continues to sparkle and this attracts the attention of the enemies to it. Thus, starfish can escape (Ganeri, 1999).

Fishes: According to the results of surveys performed, it is revealed that the 70 % of the fishes inhabiting 600 m below seas have lighting organs (Widder, 2001).

Lighting organs of *Ceratoscopelus maderensis* (Myctophidae), located on both sides of the body, give off various colors of light like ampoules arranged in a row (Fig. 2g). Some fishes lighting organs of which are accumulated around the mouth live on small fishes coming by the deception of light. There is an extremity resembling to fishing rod on the head of anglerfish *Lophius piscatorius* (Lophiidae) and generally is a sparkling bubble at the point of this extremity (Fig. 2h).

Argentina sphyraena (Argentinidae) like many other deep-sea fishes, have photophores which produce lights over the lower part of their abdomen. The number of these photophores can reach 100. These fishes give off faded blue-light which is produced as a result of chemical reactions of photophores, suited to day-light and hides them against enemies in the deep waters (Ganeri, 1999).

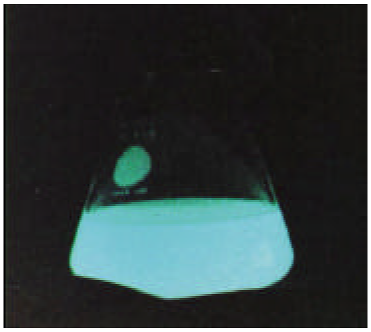
Some fishes inhabiting shallow waters might produce light, as well. One of them whose light is the brightest is eyelight fish *Photoblepharon palpebratus* (Anomalopidae). The light of this fish inhabiting in coral reefs is so bright that can be realized as far as 30 m.

Eyelight fish uses its light to find its hunts, to bewilder its enemies and to communicate with the others of the same species. Its luminous lights are produced by the organs situated around eyes (Fig. 2i). These organs carry millions of bacteria to give off light. These bacteria live on sugar and oxygen dispersed in blood. Eyelight fish can turn on/off and direct the light wherever it wants, thanks to its eyelids serving as a kind of shutter. In fact, the light produced by just a single anglerfish is enough to illuminate a small room.

It is seen in the region where eyelight fish inhabits that the people remove the sparkling part of the fish and use this part as bait while hunting, due to the fact that it could stay luminous for hours after the death of fish (Ganeri, 1999).

APPLICATIONS

In the 1870's, some luminescent bacteria were grown in culture conditions. The present tally of cultivable marine species is about 10, three of them assigned to the genus *Photobacterium*, five to *Vibrio* and two to *Shewanella* (Herring, 2002). Figure 3a and b show cultured bacteria.



(a)

(b)

Fig. 3: Cultures of *Photobacterium phosphoreum* (a) and *Vibrio fischeri* strain Y-1 (b) by their own light

Luciferase genes were cloned in the 1980's; and this has provided an almost unique range of tools for studying the regulations of intracellular processes and the fate of different bacteria under a wide variety of conditions.

Bioluminescent marine bacteria have potential biotechnological applications, mainly in the detection of mutagenic and toxic compounds in marine environments (Wegrzyn and Czyz, 2002)

Bioluminescence, with the increasing knowledge about its molecular and genetical characterization, could be used in different fields of application (Sukatar and Karaboz, 2001).

CONCLUSION

Bioluminescence is the main source of lights for deep waters. Although bioluminescence is found in many fish species, there could be undiscovered marine species which have this peculiarity.

Prospective discovery of bioluminescent organisms, other than the known species, might lead to some unpredictable developments in the future. Perhaps, cultures of bioluminescent aquatic organisms will be under attention and the farming of the macroscopic bioluminescent aquatic organisms which especially inhabit shallow waters for the purpose of exhibition will be able to bring benefits to the aquarium sector.

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