

Bioluminescence in Aquatic Ecosystems: Mechanisms, Roles, and Ecological Consequences

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Abstract

Bioluminescence, the generation and release of light by living organisms, is a prevalent occurrence in marine ecosystems, significantly influencing the survival and interactions of many marine species. It fulfils multiple roles, including communication, predation, camouflage, and mating. The molecular mechanisms of bioluminescence are intricate and have evolved throughout time to meet the requirements of many marine species. The present communication highlights the importance of bioluminescence in marine ecosystems, emphasizing its ecological functions. Ongoing investigation of bioluminescence will augment our comprehension of marine environments and various ecological ramifications.

Keywords: *Bioluminescence, Aquatic ecosystem, Luciferin, Luciferase.*

Introduction

Bioluminescence, characterized by the capacity of living creatures to produce visible light, is a prevalent occurrence across biological domains. Bioluminescent creatures inhabit in terrestrial and aquatic environments. Nonetheless, aquatic organisms are solely confined to marine settings, and a freshwater bioluminescent system has yet to be documented (Kahlke and Umbers, 2016). Bioluminescent organisms occupy nearly all marine aquatic environments, ranging from the epipelagic zone to the deep-sea benthos and freshwater ecosystems. A variety of creatures, including insects like fireflies and glow-worms, as well as certain fungi, have evolved the capability to emit light, leveraging its numerous functional benefits across various geographic areas (Schramm and Weib, 2024). Bioluminescence fulfils various ecological roles among diverse taxa, encompassing predator-prey dynamics, communication and mating, camouflage and counterillumination, as well as toxin-excretion signalling. Disruptions including light pollution, anthropogenic climate change, and nutrient loading can modify bioluminescent dynamics and affect critical ecological processes in aquatic systems (Martini *et al.*, 2019). Bioluminescence serves a crucial ecological function in

aquatic ecosystems, influencing intricate interactions that affect evolutionary pathways and population dynamics (Valiadi and Iglesias-Rodriguez, 2013).

Almost all aquatic bodies are inhabited by several plants, animals and microbes. Among them bioluminescence is exhibited by certain species of bacteria, fungus, dinoflagellates, sponges, jellyfish, deep-sea corals, annelids, shrimp, squids, gastropods, brittle stars, tunicates, and fish (Ramesh, 2020). Each of them also contributes to the overall fitness and variety of a healthy ecosystem by facilitating natural resources and nutrient supply. Though plants are unable to produce bioluminescence but bioluminescent organisms are severely dependent on plants. In an aquatic ecosystem, plants at various seral stages adapt to ensure that all components receive adequate natural resources from the habitat (Mazumder *et al.*, 2021). The presence of aquatic macrophytes is usually considered as asset for aquatic habitat but some cases they may adversely affect the aquatic systems (Mazumder and Sarkar, 2020). Bioluminescence is categorized into two categories depending on biochemical origins: primary bioluminescence, where organisms produce their own light, and secondary bioluminescence, when light is generated by symbiotic bacteria (primary bioluminescents) (Schoenemann *et*

al. 2015). Numerous terrestrial and marine creatures remain untested to confirm their capacity to create bioluminescence under natural or stressful conditions. In marine environments, luminous species are crucial to ecosystem functionality, and bioluminescence is an essential element of brackish water ecosystems (Mashukova *et al.*, 2023). The prevalence of bioluminescent organisms in watery environments and terrestrial habitats is virtually insignificant (Haddock *et al.*, 2010).

Mechanisms of Bioluminescence in Aquatic Organisms

Bioluminescence refers to the emission of light by living organisms as a result of biochemical processes. The phenomenon is prevalent throughout marine environments and in deeper freshwater habitats, where ambient light levels are limited. Light production strategies differ substantially among organisms, even when colour and intensity are comparable. Two primary categories of bioluminescent reactions have been distinguished: autogenic, in which the organism itself generates light; and associative, in which there is a transfer of excited states responsible for light emission between different species (Timsit *et al.*, 2021). Bioluminescence exhibits emission energy throughout the whole optical spectrum, spanning from the deep blue region at approximately 430 nm to the near infrared at roughly 700 nm (Schramm and Weib, 2024). Biochemically generated luminescence is a ubiquitous occurrence in the deep water, particularly at depths over around 1000 meters. The existing lack of data regarding the molecular mechanisms of their luminescence prevents a thorough analysis of these systems at present time.

Bioluminescence is fundamentally a chemiluminescent reaction catalyzed by enzymes in living organisms. The process entails a chemical reaction that produces excited state molecules. Upon returning to their ground state, these excited state molecules release light. The biochemical processes responsible for light emission involve a luciferin, a substrate that emits light, and a luciferase, an enzyme that catalyzes oxidation to generate illumination (Vysotski, 2023). The initiation of every bioluminescence process involves a chemical substance known as luciferin, whose molecular structure may differ across various organisms (Schramm and Weib, 2024). Nine distinct luciferins and their corresponding luciferases have been identified in bioluminescent organisms, with many additional examples anticipated (Kaskova *et al.*, 2016).

The luciferins evolve via various molecular mechanisms that may also be present in non-luminescent organisms, whereas luciferases represent a specific instance of enzyme evolution that is not directly linked to their biochemical origins. The relatively small number of independently derived luciferins and luciferases indicates that bioluminescence has arisen multiple times throughout evolutionary history (Kaskova *et al.*, 2016). Upon binding with oxygen, luciferin generates oxyluciferin and releases energy as light. The structural distinction between luciferin and oxyluciferin in bioluminescent systems is characterized by the removal of a carboxyl group from luciferin and the generation of a ketone. The attributes of bioluminescence can indicate the condition of the organism and, by extension, the condition of the surroundings (Mashukova *et al.*, 2023). Numerous bioluminescent creatures with unique chemical processes and diverse chemistry remain to be identified in protected aquatic regions and the deep sea.

Ecological Roles of Bioluminescence

Bioluminescence serves a crucial ecological function in aquatic ecosystems, facilitating intricate interactions that influence evolutionary pathways and population dynamics (Valiadi & Iglesias-Rodriguez, 2013; Amaral *et al.*, 2024). The ecological significance of bioluminescence in the ocean is seen in the prevalence of light-emitting organisms in open waters; luminous fish and crustaceans prevail in biomass, while bacteria and dinoflagellates are predominant in abundance (Widder, 2016). In marine ecosystems, light significantly influences the spatial distribution of marine communities (Martini and Haddock, 2017). Consequently, the luminous radiance of bioluminescence attracts predators. The development of camouflage via counter-illumination and transparency complements the aspect of luminosity. The extended wavelength of bioluminescence observed in deceased individuals in the light enhances the likelihood of escape from bard clonal species (Martini *et al.*, 2019).

Luminescent substances may be discharged directly into the water or sequestered within cells known as photocytes (Widder, 2016). Bioluminescent signalling is among the most prevalent communication methods utilized by marine species. Bioluminescence plays a significant role in interspecies interaction throughout ecosystems (Mashukova *et al.*, 2023).

➤ Interactions Between Predators and Prey

Bioluminescence is crucial in marine food webs, especially within deep-sea environments. Organisms

across many trophic levels, ranging from plankton to apex predators, employ bioluminescence for multiple functions related to food web. Bioluminescence affects predator-prey interactions in marine habitats. In the abyssal ocean, where illumination is limited, predators depend on bioluminescence for hunting, whereas prey utilize bioluminescent signals to escape from predators (Campbell, 2022). The interaction between bioluminescent predators and prey enhances the richness of marine environments, prompting evolutionary adaptations in both predator and prey species. Predator-prey interactions provide a crucial ecological function influenced by light emission. Bioluminescence may function as a deterrent to predators in prey that remain un-eaten, offering the possibility of 'automatic' communication. Squids, copepods, shrimps, myctophids, siphonophores, ctenophores, chaetognaths, and numerous fish species employ a vivid flash of bioluminescence to confuse an attacking predator (Haddock *et al.*, 2010). In these instances, the organisms frequently expel a bioluminescent secretion or engage in the autotomy of luminescent appendages (Robison *et al.*, 2003; Bush *et al.*, 2009). In these scenarios, luminescence may be anticipated from bioluminescent species under predation threat; however, based on existing knowledge, this form of autonomic communication has not yet been documented in the literature. The strategy of resisting predation through the combination of luminescence and cryptic coloration continues to be a focus of research for dinoflagellates. The phrase "bioluminescence" typically evokes ideas of beauty and wonder; nevertheless, in the realm of predator-prey dynamics, these light displays possess a more dismal essence. Millions of years of evolution have resulted in bioluminescent organisms capable of generating spectacular light shows. Bioluminescence observed during predator-prey interactions occurs within a timeframe of 0.1 to 2.0 seconds. It can assist in finding food, either by integrated headlights or by employing luminescent lures (Widder, 2010). Various crustaceans and fish emit distinct colours of light; for instance, the Japanese crustacean *Dromidia antillensis* generates bluish-white light, the Japanese krill *Euphausia pacifica* also produces bluish-white light, and the lanternfish *Miktonia microcygnus* emits nearly monochromatic violet light (Turner *et al.*, 2009). Red bioluminescence, or luciferin, is not observed in natural settings; thus, marine creatures are unable to perceive red warning bioluminescence. Organisms like *Vanessa antipa* experience significantly longer

exposure durations of 3 to 6 seconds during predator-prey interactions compared to bioluminescent crustaceans and fishes. Groups of various crustaceans, fishes, and euphausiids are often bitten but not consumed, thereby displaying warning bioluminescence. Schooling behavior may significantly influence the evasion strategies of numerous odontocetes, elasmobranchs, and teleosts (Martini *et al.*, 2019).

Bioluminescence is not merely a deterrent to predators; it is a multifaceted and efficient approach that enhances survival in intricate predator-prey dynamics. Bioluminescent species are documented to function as lures to attract prospective predators during predator-prey interactions, based on both theoretical and experimental studies. Species exhibiting bioluminescent epidermal cells, bioluminescent mucus, and bioluminescent structures are documented in these particular predator-prey interactions (Davis *et al.*, 2014).

➤ **Communication and Mating**

Communication and reproduction serve crucial ecological functions for bioluminescent organisms within maritime habitats. A study on deep-sea life indicated that roughly 80% of marine eukaryotic taxa had bioluminescence, with an estimated 95% of taxa in the epipelagic zone displaying this characteristic (Davis *et al.*, 2014). Numerous animals without bioluminescence may yet be directly or indirectly linked in symbiotic interactions with luminous creatures. Species-specific bioluminescence patterns have been associated with reproductive isolation, facilitating population divergence and ultimately promoting speciation. Bioluminescence has been utilized for communication across various taxonomic groupings, including bacteria, dinoflagellates, ctenophores, and multiple families of fish. Unicellular organisms may react to the bioluminescence of conspecifics, suggesting that such luminescence serves as a signalling mechanism, but the specifics of the response remain inadequately comprehended (Timsit *et al.*, 2021). Bioluminescent signals generated by unicellular creatures in the presence of multicellular animals may contribute to or engage with bigger populations and communities, however the function of these molecules remains ambiguous. These signals may captivate larger consumers, thereby broadening the dispersion of microbial biomass.

Camouflage and Counter-illumination

Bioluminescence camouflage, a type of counter-illumination, diminishes the likelihood of discovery by predators or prey (Davis *et al.*, 2014). Counter-illumination necessitates comprehension of ambient light intensities across several spatial and temporal dimensions. Counter-illumination predominantly transpires in the pelagic zone, where downwelling light from the sun or moon provides essential information regarding ambient light conditions to the organism. Numerous open-ocean macroplankton utilize either defensive or reproductive counter-illumination. In high-light situations, when the vertical encounter rate with possible predators is elevated, downwelling irradiance increases, making defensive bioluminescent counter-illumination more probable (Martini *et al.*, 2019). Benthic marine creatures also utilize this phenomenon; however, only 2–3% of benthic species exhibit bioluminescence. Furthermore, numerous shallow-water ecosystems are primarily influenced by direct ultraviolet radiation from the sun or reflected ultraviolet radiation from the moon. Numerous fish, crabs, and cephalopods employ ventrally located photophores to conceal themselves from deep-sea predators under the illumination of the moon and stars (Jones and Nishiguchi 2004; Kubodera *et al.*, 2007).

Bioluminescence Across Aquatic Habitats

Bioluminescence manifests in markedly varied patterns throughout aquatic settings, particularly across marine and freshwater ecosystems. Bioluminescence, however, varies significantly among marine settings, with distinctions noted among open ocean, coastal communities, and benthic organisms. Aquatic species exhibit bioluminescence in all examined instances (Martini *et al.*, 2019). Bioluminescence is observed in 57% of marine phyla (59% of deep-sea phyla) and approximately 30% of freshwater lineages, while there is taxonomic diversity in the proportion of species that exhibit luminescence. The coastal zone, encompassing brackish seas, serves as a haven for bioluminescence, with taxa dependent on bioluminescence constituting a larger percentage of identified species. It is expected that the proportion of active bioluminescent species in coastal oligotrophic systems exceeds 50% on average. An empirical approach on a worldwide scale demonstrates analogous disproportionate coastal engagement throughout maritime domains. The comprehensive framework categorizes bioluminescent species based on their primary habitat (open ocean, benthic, and freshwater), as each environment exhibits unique eco-evolutionary processes. The marine open ocean constitutes 65% of habitable volume but accounts for only 27% of known species, with extensive scaling relationships suggesting

that total global species richness approaches 500 billion. In marine, coastal, and freshwater ecosystems, bioluminescence is essential to community dynamics and influences the ecological function of light. Coastal, benthic, and freshwater habitats are frequently neglected in assessments of global bioluminescent biodiversity. A thorough comprehension of bioluminescence in aquatic ecosystems encompasses the examination of light-emitting functions, with a particular focus on notable open-ocean taxa such as dinoflagellates and copepods. It is essential to consider the multi-scale prevalence of bioluminescence and delineate its taxonomic, functional, and biogeographic distribution throughout diverse aquatic habitats (Valiadi & Iglesias-Rodriguez, 2013).

➤ **Marine Open Ocean**

Bioluminescence affects marine predator-prey dynamics, communication, and competition for resources. Bioluminescent species in open ocean environments have unique selection pressures associated with interspecific interactions, light wavelength absorption relationships, and morphological adaptations (Martini *et al.*, 2019). The energetic expense of light creation is posited to influence organismal light production and pigmentation. Open-ocean bioluminescence appears earlier in the taxonomy of luminous creatures than in the benthic habitat. Organisms exhibiting luminescence in the deep sea are less prevalent and distributed than their non-luminescent counterparts, however they are taxonomically diverse (Valiadi and Iglesias-Rodriguez, 2013).

➤ **Coastal and Benthic Communities**

Bioluminescence is prevalent in coastal marine animals, especially in dinoflagellates residing in shallow waters near the shore. The marine coastal zone, ranging from the intertidal area to just beyond the continental shelf, is characterized by elevated concentrations of bioluminescent organisms. These taxa encompass both extensively researched organisms such as the dinoflagellate *Gonyaulax polyedra* and lesser-known species like the luciferin-luciferase-producing ciliate *Fabrea salina*. The dinoflagellate *Noctiluca scintillans*, prevalent in coastal areas and frequently associated with the "sea sparkle" phenomenon, has attracted significant interest because to its comparatively uncomplicated bioluminescent system (Valiadi & Iglesias-Rodriguez, 2013). In contrast, the open ocean typically harbors fewer luminous taxa, with bioluminescence significantly diminished throughout the water column when coastal waters and continental slopes are omitted.

Conversely, numerous benthic creatures, whether motile or sessile, have the capability to produce light. When examining these taxa as components of coastal and benthic assemblages, it is important to recognize that their actions concerning water column emissions may vary by region. Fauna residing on continental slopes typically exhibit a more extensive array of bioluminescent behaviors compared to those found at the beach, where bioluminescence often serves as a long-distance signal to optimize energy conservation during interactions with organisms that are not directly confronted. Considering that distinctive coastal and benthic assemblages are frequently utilized by educational and research institutions, enhancing our comprehension of the ecology of these species is a rational subsequent action. Coastal and benthic drifters are significantly relevant to the study of marine bioluminescence (Martini *et al.*, 2019).

➤ Aquatic Freshwater Systems

Bioluminescence occurs in freshwater creatures; however, it is less understood than in marine settings. Only a limited number of freshwater species have been identified as bioluminescent (Valiadi and Iglesias-Rodriguez, 2013). Organisms possessing cytoplasmic luciferin-luciferase bioluminescence systems are believed to be exclusively found in the dinoflagellates *Gonyaulax* and *Pyrocystis* (Martini *et al.*, 2019). Organisms from these genera are frequently referenced as bioluminescent entities in freshwater ecosystems; yet, there is a paucity of research connecting environmental stimuli to these phenomena. Free-living bioluminescent dinoflagellates are believed to inhabit only brackish to marine settings. Isolated reports of bioluminescence in copepods from East African lakes also exist. Bioluminescence is thus regarded as un-common in the majority of lakes and rivers.

Ecological Consequences of Bioluminescence

Bioluminescence is an ecological characteristic pertinent to freshwater and marine aquatic environments. Light is utilized to augment ecological linkages via predator-prey interactions and mating selection. The function of bioluminescence in ecological interactions varies with the environment; for

instance, species in pelagic zones employ bioluminescence more often than those in deep-sea floor habitats. In the latter, the presence of boulders, mud, and turbidity constrains the transmission of self-generated light.

Certain aquatic organisms exhibit bioluminescence, while some species do not luminesce during a certain ontogenetic stage but generate light at either an earlier or later time. The taxa contributing to ecological connections among surface bioluminescent organisms in freshwater environments remain mostly unidentified. Comprehending the ecological significance of bioluminescence in deep-sea benthic ecosystems is crucial, given that numerous studies indicate that human-induced stresses may profoundly affect these habitats. In response to the rising frequency of deep-sea resource explorations, diverse approaches for studying bioluminescence have been established, such as calculating distribution abundances. These analytical advancements enhance the comprehension of the ecological significance of bioluminescence in marine open ocean, coastal, benthic communities, and interior freshwater ecosystems (Valiadi and Iglesias-Rodriguez, 2013).

The ecological interactions stemming from bioluminescence are notably intriguing and varied; nonetheless, many remain enigmatic due to insufficient in-situ research.

Conclusion

Bioluminescence is a unique expression of living organisms that has developed throughout several evolutionary lineages due to environmental factors and selective forces. Significant attention has been directed towards bioluminescence in aquatic ecosystems, where this phenomenon is prevalent in both marine and freshwater environments, serving as an adaptation to darkness. The majority of aquatic creatures capable of bioluminescence exhibit at least one bioluminescent characteristic. Marine habitats established the first framework for the emergence of bioluminescence, and this phenomenon remains a subject of investigation in marine creatures.

REFERENCE

- Amaral, D.T., Kaplan, R.A., Takishita, T.K.E. *et al.*, (2024). Glowing wonders: exploring the diversity and ecological significance of bioluminescent organisms in Brazil. *Photochem Photobiol Sci* 23, 1373–1392. <https://doi.org/10.1007/s43630-024-00590-x>.
- Bush, S., Robison, B., Cadwell, R. (2009). Behaving in the dark: locomotor, chromatic, postural, and bioluminescent behaviors of the deep-sea squid *Octopoteuthis deletron* Young 1972. *Biol Bull.* 216:7–22. <https://doi.org/10.2307/25470719>.
- Campbell, J. (2022). The Role of Bioluminescence in Marine Ecosystems. *American Journal of Biological Sciences*. 3(10):1-5.
- Davis, M.P., Holcroft, N.I., Wiley, E.O. *et al.*, (2014) Species-specific bioluminescence facilitates speciation in the deep sea. *Mar Biol*. 161:1139–1148. <https://doi.org/10.1007/s00227-014-2406-x>.

- Haddock, S.H.D., Moline, M.A., and Case, J.F. (2010) Bioluminescence in the Sea. *Annu Rev Marine Sci.*2:443–493. <https://doi.org/10.1146/annurev-marine-120308-081028>.
- Jones, B., and Nishiguchi, M. (2004). Counterillumination in the Hawaiian bobtail squid, *Euprymna scolopes* Berry (Mollusca: Cephalopoda) *Mar Biol.* 144:1151–1155. <https://doi.org/10.1007/s00227-003-1285-3>.
- Kahlke, T., and Umbers, K.D.L. (2016). Bioluminescence. *Curr. Biol.* 26(8): R313–314.
- Kaskova, Z.M., Tsarkova, A.S., and Yampolsky, I.V. (2016). 1001 lights: luciferins, luciferases, their mechanisms of action and applications in chemical analysis, biology and medicine. *Chem. Soc. Rev.* 45(21):6048–6077. <https://doi.org/10.1039/c6cs00296j>.
- Kubodera, T., Koyama, Y., and Mori, K. (2007). Observations of wild hunting behaviour and bioluminescence of a large deep-sea, eight-armed squid, *Taningia danae*. *Proc Biol Sci.* 274:1029–1034. <https://doi.org/10.1098/rspb.2006.0236>.
- Martini, S., and Haddock, S. (2017). Quantification of bioluminescence from the surface to the deep sea demonstrates its predominance as an ecological trait. *Sci Rep* 7:45750. <https://doi.org/10.1038/srep45750>.
- Martini, S., Kuhnz, L., Mallefet, J., and Haddock, S. H. D. (2019). Distribution and quantification of bioluminescence as an ecological trait in the deep-sea benthos. *Scientific reports.* 9(1):14654. <https://doi.org/10.1038/s41598-019-50961-z>.
- Mashukova, O., Silakov, M. and Temnykh, A. (2023) Ecological role of bioluminescence of Black Sea ctenophores. *Biophys Rev* 15, 947–954 (2023). <https://doi.org/10.1007/s12551-023-01155-5>.
- Mazumder, M., and Sarkar, A.K. (2020) Ecological status of Angiospermic macrophytes in Retention Ponds and Drainage Ditches of Jalpaiguri District, West Bengal, India. *Indian Forester.* 146(3): 226-234.
- Mazumder, M., Dey, M., and Sarkar, A.K. (2021) Phytosociology of Associated Aquatic Macrophytes coexisted with *Nymphoides aurantiaca* (Dalzell) Kuntze in Eastern Himalayan Foot Hill plain of West Bengal, India. *Bull. Env. Pharmacol. Life Sci.*, 10 (10): 53-60.
- Ramesh, C. (2020). Terrestrial and marine bioluminescent organisms from the Indian subcontinent: A review. *Environmental Monitoring and Assessment.* 192(12): 747
- Robison, B.H., Reisenbichler, K.R., Hunt, J.C., et al., (2003). Light production by the arm tips of the deep-sea cephalopod *Vampyroteuthis infernalis*. *Biol Bull.* 205:102–109. <https://doi.org/10.2307/1543231>.
- Schoenemann, B., Clarkson, E. N.K., and Horváth, G. (2015). Why did the UV-A-induced photoluminescent blue–green glow in trilobite eyes and exoskeletons not cause problems for trilobites? *Peer J.* 3: e1492. <https://doi.org/10.7717/peerj.1492>.
- Schramm, S. and Weib, D. (2024). Bioluminescence - The Vibrant Glow of Nature and its Chemical Mechanisms. *Chem Bio Chem.* 25: e202400106. <https://doi.org/10.1002/cbic.202400106>.
- Srivastava, A., and Katiyar, K. (2021). The Ecology of Bioluminescence. In Suzuki, H. and Ogoh, K. (Eds.) *Bioluminescence-Technology and Biology.* In *Tech Open.* <https://doi.org/10.5772/intechopen.96636>.
- Timsit, Y., Lescot, M., Valiadi, M., and Not, F. (2021). Bioluminescence and Photoreception in Unicellular Organisms: Light-Signalling in a Bio-Communication Perspective. *International journal of molecular sciences.* 22(21):11311. <https://doi.org/10.3390/ijms22111311>.
- Turner, J.R., White, E.M., Collins, M.A., Partridge, J.C., Douglas, R.H. (2009). Vision in lanternfish (Myctophidae): adaptations for viewing bioluminescence in the deep-sea. *Deep-Sea Research I* 56:1003–1017
- Valiadi, M., and Iglesias-Rodriguez, D. (2013). Understanding Bioluminescence in Dinoflagellates—How Far Have We Come? *Microorganisms.* 1(1):3-25. <https://doi.org/10.3390/microorganisms1010003>.
- Vysotski E.S. (2023). Bioluminescent and Fluorescent Proteins: Molecular Mechanisms and Modern Applications. *International journal of molecular sciences.* 24(1): 281. <https://doi.org/10.3390/ijms24010281>.
- Widder, E. A. (2010). Bioluminescence in the Ocean: Origins of Biological, Chemical, and Ecological Diversity. *Science* 328:704. <https://doi.org/10.1126/science.1174269>.

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