



Perspectives on marine dinoflagellate bioluminescence: Is the current prevalence along the Indian waters only reckoned with aesthetic pleasure?

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Received 31 January 2022; revised 04 June 2023

A review of bioluminescence blooms specific to Indian waters was undertaken, aiming to identify the prevailing species accountable for these occurrences and to assess whether there is an increasing trend in bioluminescence bloom reports in India. Despite the frequent prevalence of bioluminescence blooms in Indian waters, there is a notable scarcity of dedicated studies exploring the bioluminescence potential of blooming species. Consequently, this review seeks to assess the frequency of bioluminescence blooms from 1890 to 2023. The review incorporates the current state of bioluminescence studies in India, presenting perspectives on the prevailing knowledge gaps within the same field. Compilation of 26 reports from over 30 locations across coastal, oceanic, and island ecosystems of India revealed a substantial increase in bloom reports post-2011, with only seven records available up to 2010. As per the reports availed, dinoflagellates – a notable planktonic community comprising species competent for Harmful Algal Blooms (HABs), toxin production and bioluminescence – is found to be the major causative organism of bioluminescence blooms along the coastal India. Despite the visual allure of bioluminescence, the deleterious impact of these dinoflagellate blooms on ecosystem functioning and the national economy necessitates significant attention. Conducting focused research on the diversity and distribution patterns, measuring bioluminescence intensity in response to different stimuli, and exploring genetic variability in bioluminescent organisms can offer essential baseline data to support and guide future research on bioluminescence.

[**Keywords:** Bioluminescence, Bloom formation, Dinoflagellate, India, Marine ecosystem]

Introduction

Bioluminescence, or the biochemical production and discharge of cold light from living organisms, is a phenomenon that has been detected in over 700 genera globally, with the large majority ($\approx 80\%$) of them inhabiting the world's oceans¹. Bioluminescent species belong to about 14 marine phyla, from bacteria to fishes², with varying photon fluxes and emission kinetics³. Bioluminescence has evolved independently several times (> 40 times) owing to the diverse chemistries of light emission systems⁴. Around 30 different bioluminescence systems are presently known⁵. The luminous reaction occurs due to the enzyme-catalysed oxidation of the substrate – luciferin by either luciferase or photoprotein. The generation and mobilisation of these molecules are energetically expensive, demanding energy equal to around 60 molecules of ATP per photon emitted⁶. Bioluminescent glows fall within the visible range of the electromagnetic spectrum, *i.e.*, 410 nm to 710 nm, and a significant proportion of the bioluminescence produced in the open ocean is blue ($\lambda = 450$ nm to

490 nm) due to its optimal transmission in seawater⁷. In contrast, green light ($\lambda = 490$ nm to 520 nm) is predominant in species residing in benthic and shallow coastal waters⁸. This is due to increased water turbidity, which causes scattering of blue light, facilitating transmission of longer wavelength - green light^{3,9}. Among the least commonly emitted colors are yellow, orange, violet, and red¹⁰⁻¹². Conformational changes in luciferins, organisation of binding proteins, and physical characteristics of light-emitting structures are identified to be the causes for this difference in emitted colours¹³.

Bioluminescence is a ubiquitous phenomenon that spans all ocean dimensions and is anticipated to serve various ecological functions, including predation, self-defense, and communication. However, during bloom events, the visibility of bioluminescence is fully enhanced. Apart from the aesthetic pleasure that bioluminescence bloom events offer, it has the potential to cause serious threats to the marine ecosystem depending upon the ecological traits of the causative species. Dinoflagellates are the major

contributors of surface bioluminescence in the oceanic as well as coastal ecosystems¹⁴. About 12 species of bioluminescent dinoflagellates are known for toxin production, and most of them have caused frequent, widespread Harmful Algal Blooms (HABs) worldwide¹⁵. A robust description of the diversity and distribution of bioluminescent organisms and their ecological traits, particularly toxin production/HAB formation, is imperative to deal with the threats they can cause. Although bioluminescence has received huge scientific attention globally, including its quantification and applications, there is a lacuna in marine bioluminescence studies from India, except for bacterial luminescence. In the present review, an attempt has been made to compile the bioluminescent bloom events recorded from the Indian waters (coastal, island, as well as oceanic) from 1890 – 2023 along with an overview of the bioluminescence studies conducted in India so far. In this article, henceforth, when referring to the term "bioluminescence blooms", it is intended to encompass both bloom and swarm events for the readers' understanding. The review also presents the natural and anthropogenic drivers responsible for triggering dinoflagellate blooms, which is the most prevalent bioluminescent group encountered along the Indian waters. The critical research gaps from Indian waters are also highlighted to facilitate future studies.

Materials and Methods

Published literature and online news reports from 1890 – 2023 were reviewed to obtain data on bioluminescence bloom events reported from the Indian waters. Given the limited scientific reports on bioluminescent blooms, online news reports have been included in compilation. The keywords 'bioluminescent blooms', 'Indian waters', 'bioluminescent dinoflagellates', 'Indian coast', and a conjugation of these terms were used to extract the data from the search engines. Ocean Data View (version 5.6.2)¹⁶ was used to plot the bioluminescence bloom records along the Indian waters. The graphs were plotted using the software OriginPro¹⁷. The year of bioluminescence bloom occurrence was taken into account while plotting the temporal variations. The species nomenclature has been updated to the current status, and the validity of each species is checked to the best of our knowledge using the species portal database, WoRMS¹⁸.

Results and Discussion

Since 1890, a total of 26 bioluminescence bloom events have been reported from the Indian waters - 15 published reports and 11 online news reports (Table 1). The causative organism of bioluminescence reported in online news reports remains largely unidentified except for a few instances of bioluminescent tides by *Noctiluca scintillans*. Although bioluminescence blooms have gained huge public interest due to their spectacular glows, in-depth studies on bioluminescence properties of the blooming-species are still lacking from the Indian waters.

Bioluminescence blooms in the Indian waters: Are dinoflagellates the primary culprit?

Bioluminescence blooms have been reported from the coastal, oceanic, and island regions of India (Fig. 1). Available reports suggest the dominance of single-species bioluminescence blooms along the Indian waters. Dinoflagellates (*Noctiluca scintillans* (Macartney) Kofoid & Swezy, 1921; *Gonyaulax spinifera* (Claparède & Lachmann) Diesing, 1866; *Proto-peridinium granii* (Ostenfeld) Balech, 1974; *Peridinium* sp.; *Pyrocystis* sp.) were the primary source of coastal bioluminescence blooms in India (Fig. 2). In contrast, bioluminescent ostracod *Cypridina dentata* (Müller, 1906) and radiozoan *Thalassicolla* sp. were reported from the northern Arabian Sea and off Andaman Island, respectively. In Kavaratti lagoon (Lakshadweep Island), the prevalence of bioluminescent ostracod *Vargula hilgendorffii* (Müller, 1890) has been reported.

Post-2011, there has been a notable increase in the number of bioluminescence bloom reports in Indian waters (Fig. 3), documented through 11 online media reports and eight scientific literatures. The probable relationship between the increasing occurrences of bioluminescence blooms and global warming has been a much debated topic recently. Increasing public interest can indeed be a factor for increased media reports on bioluminescence sightings in recent times. Also, technological advancements have increased the ease with which social media could propagate the news on bioluminescence. Thus, there is uncertainty regarding the surge in bioluminescence sightings with an increase in global warming, and the same does not establish the chance of a boom in bioluminescent organisms with future warming.

Table 1 — List of bioluminescence blooms reported from India during the years 1890 – 2023. The data has been collected from various published literature and online media reports

Sl. No.	Causative organism	Year and month of bioluminescence bloom events	Area of bioluminescent bloom occurrence	References
1	<i>Thalassicolla</i> sp.	1890 November	Off Andaman Islands, Bay of Bengal	Alcock ⁴⁴
2	<i>Peridinium granii</i> Ostenfeld, 1907 (Accepted name: <i>Protoperidinium granii</i> (Ostenfeld) Balech, 1974)	1958 November	Visakhapatnam, Andhra Pradesh	Ganapati <i>et al.</i> ⁶⁵
3	<i>Peridinium</i> sp. & <i>Pyrocystis</i> sp.	1965 February to April	Mandapam, Tamil Nadu	Nair <i>et al.</i> ⁶⁶
4	<i>Cypridina dentata</i> (Müller, 1906)	1973 December to 1974 May	Northern Arabian Sea	Daniel & Jothinayaoam ⁴⁵
5	<i>Noctiluca miliaris</i> Suriray, 1816 (Accepted name: <i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921)	1974 February	Northern Arabian Sea	Daniel & Nagabhushanam ⁶⁷
6	<i>Noctiluca miliaris</i> Suriray, 1816 (Accepted name: <i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921)	1988 October	Off Thoothukudi (and nearshore areas of Kayalpatnam, Tiruchendur, Manapad, Idinthakarai and upto Kanyakumari), Tamil Nadu	Gopinathan <i>et al.</i> ²⁶
7	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921	2008 August	Off Kochi, Kerala	Padmakumar <i>et al.</i> ⁶⁸
8	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921	2015 July	Off Alappuzha, Kerala	Padmakumar <i>et al.</i> ⁶⁹
9	<i>Cypridina hilgendorffii</i> Müller, 1890 (Accepted name: <i>Vargula hilgendorffii</i> (Müller, 1890))	2015 October	Kavaratti Lagoon, Lakshadweep Islands	Ratheesh Kumar <i>et al.</i> ⁴⁶
10	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921	2016 November	Juhu beach, Maharashtra	The Hindu ⁷⁰
11	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921	2016 September	Chavakkad, Kerala	Vijayalakshmy <i>et al.</i> ⁷¹
12	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921	2017 May	Juhu beach, Maharashtra	India Times ⁷²
13	-	2018 September	Coastal belt from Mangaluru to Udupi, Karnataka	Bangalore Mirror ⁷³
14	-	2019 April	Juhu Beach, Maharashtra	DNA ⁷⁴
15	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921	2019 August	Chennai (Kovalam to Thiruvannamiyur coast), Tamil Nadu	India Today ⁷⁵
16	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy, 1921	2019 August	Chennai coast, Tamil Nadu	Mishra <i>et al.</i> ⁷⁶
17	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy	2019 May	Kochi, Kerala	Parvathi <i>et al.</i> ⁴⁷
18	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy	2019 September	Gulf of Mannar, Tamil Nadu	Raj <i>et al.</i> ⁷⁷
19	-	2020 March	Kumbalangi, Kerala	ONmanorama ⁷⁸
20	<i>Gonyaulax spinifera</i> (Claparède & Lachmann) Diesing, 1866	2020 March	Cochin estuary, Kerala	Vishal <i>et al.</i> ²⁸
21	-	2020 November	Karnataka coast (Padukere, Udupi, Mattu, Karwar, Kumta, and Surathkal)	Daijiworld.com ⁷⁹
22	-	2020 November	Juhu in Maharashtra to Betalbatim in Goa	Financial Express ⁸⁰
23	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy	2020 November	Juhu beach, Devgad, Velas, and Murud in Maharashtra; Padukere beach in Karnataka	The Times of India ⁸¹
24	<i>Noctiluca scintillans</i> (Macartney) Kofoid & Swezy	2021 December	Varkala, Kerala	Samanta <i>et al.</i> ⁸²
25	-	2023 April	Bhemili beach, Andhra Pradesh	The New Indian Express ⁸³
26	-	2023 March	Kumbalangi, Kerala	The Hindu ⁸⁴

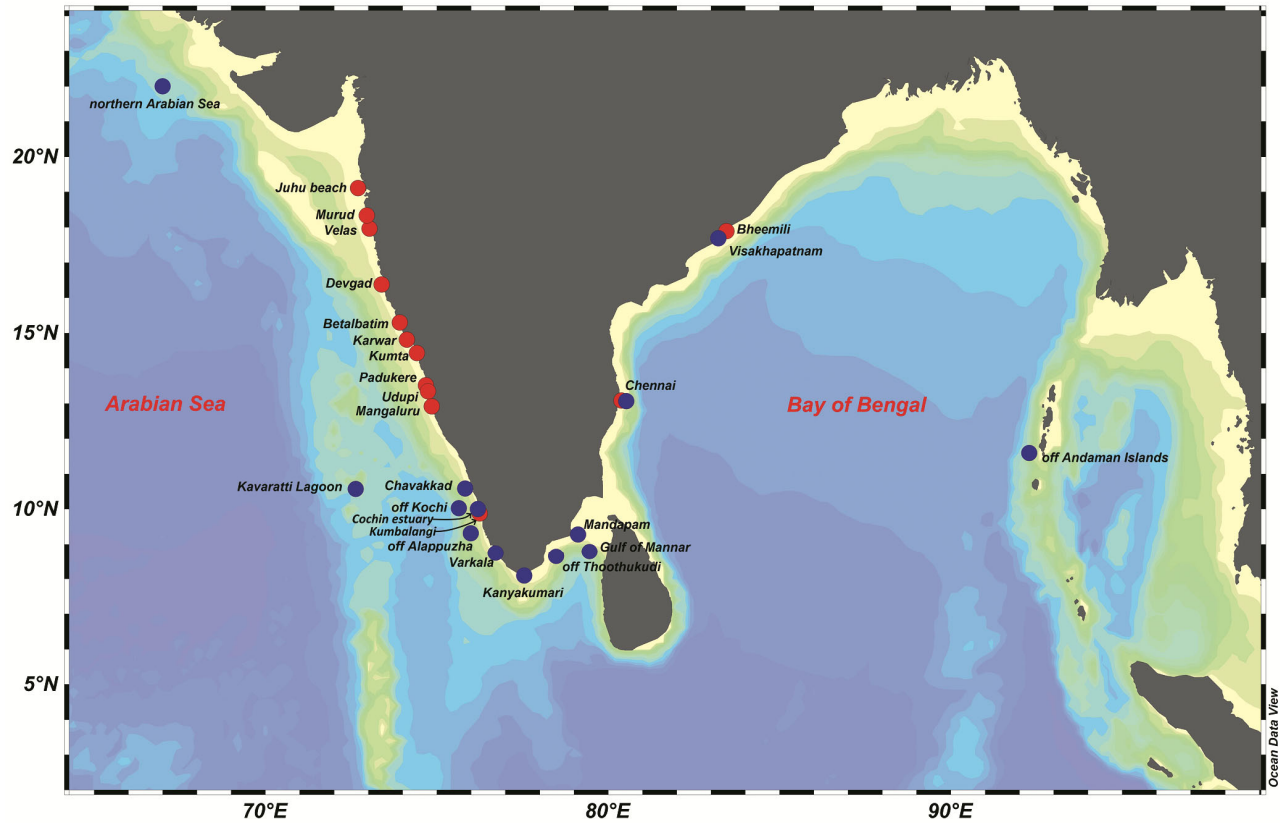


Fig. 1 — Bioluminescence blooms reported along the Indian waters from 1890 – 2023. The red dots represent online media reports and blue dots represent reports from published literature. To prevent cluttering, neighbouring locations in close proximity have been excluded from the map. Comprehensive details for all locations have been provided in Table 1

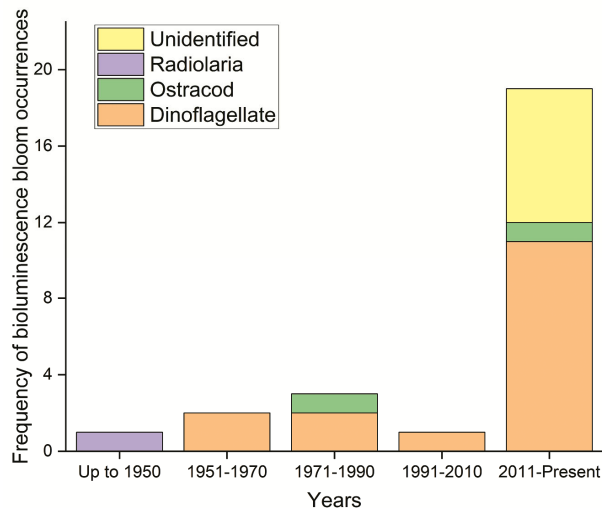


Fig. 2 — The prevalence of dinoflagellates, ostracods, and radiolaria in bioluminescence bloom events spanning 1890 to 2023. The graph also incorporates unidentified groups

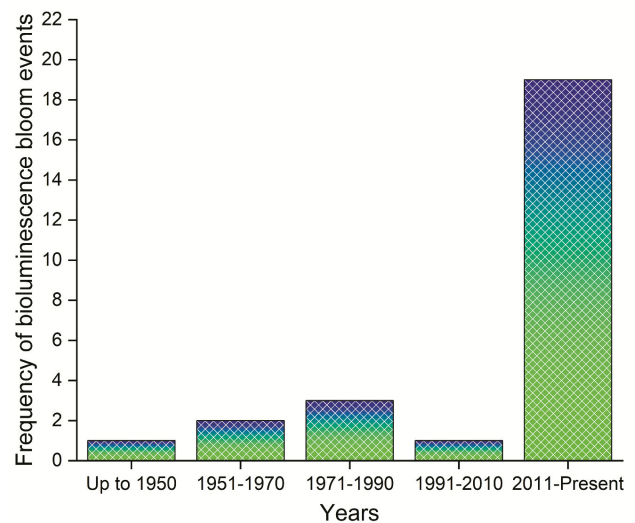


Fig. 3 — Temporal variation in the frequency of bioluminescence bloom events along Indian waters

An overview of the mechanism of dinoflagellate bioluminescence

Bioluminescence in any organism can be attributed either to the presence of luciferin–luciferase system or bacterial symbionts. The majority are capable of

producing luciferin (substrate) and luciferase (enzyme); whereas, certain species of squids (*e.g.*, members of the family Sepiolidae) and fishes (*e.g.*, *Photoblepharon* spp.) exhibit bacterial

bioluminescence¹³. Light production in the ocean is predominantly attributed to five luciferins – bacterial luciferin, dinoflagellate luciferin, coelenterazine, *Cypridina* luciferin (vargulin) and *Odontosyllis* luciferin^{4,19}. The other known marine luciferins are derived from bivalvia, hemichordata, and ascidians. Several other luciferins are to be discovered, mainly from nemerteans, molluscs, and echinoderms⁴. In dinoflagellates, light production is pH-dependent and takes place in characteristic cellular organelles called scintillons. The light emission system of most dinoflagellates contains luciferin, luciferase, and a luciferin binding protein²⁰. The ecological role of bioluminescence is not yet understood clearly. Although, bioluminescence is widely thought to be a survival strategy (burglar alarm or startle effect) in dinoflagellates, there are numerous uncertainties surrounding this concept, and it has not been conclusively proven¹⁴. Mechanical stimulations such as the movement of ships, moving organisms, and waves have been identified to be the major cause of light emission²¹. These hydrodynamic turbulence activates the G-protein coupled receptor in the dinoflagellates cell membrane. The subsequent increase in the cytoplasmic-Ca²⁺ concentration results in the generation of an action potential across the cell's vacuolar membrane. This results in an inflow of protons into the scintillons from the acidic vacuoles, leading to a drop in pH (from pH 8 to pH 6), and triggers the activation of the luciferin-luciferase system, resulting in light emission²⁰. Later, in 2016, attempts have been made to address the bioluminophore and 'Dexter energy transfer' mechanism in bioluminescent dinoflagellates²². Nonetheless, numerous enigmas persist regarding the exact mechanism of dinoflagellate bioluminescence: the presence or absence of peroxidic intermediate, the chemical processes involved in the restoration of acidic scintillons to their original pH, crystal structure of luciferin-luciferase complex, chemical nature of oxyluciferin, the fate of protons (other than those involved in water production), are worth mentioning^{4,20}.

Bioluminescence beyond the shimmering glow

Dinoflagellates constitute a frequent element of marine plankton, recognised for their significant contributions to biogeochemical cycling, bioluminescence, toxin production, and HABs^{20,23}. Approximately 1555 species of dinoflagellates are

known to inhabit the marine ecosystem²⁴. Among the 70 known species of bioluminescent dinoflagellates, around 12 species are recognised for toxin production¹⁵. They produce two classes of toxins, saxitoxin and yessotoxin. These toxic-bioluminescent dinoflagellates are often found to cause widespread HABs worldwide. Blooms enhance the visibility of bioluminescence and several attempts have been made to understand the environmental drivers, ecosystem degradation and socio-economic impacts of HABs from India. However, the possible role of bioluminescence in the growth and sustenance of HABs is largely understudied. A recent investigation proposes that brighter bioluminescence induced with copepodamides in dinoflagellate *Lingulodinium polyedra* stimulates burglar alarm response in grazers causing rejection of these brightly glowing cells. The consequent selective feeding of alternate non-luminous prey by grazers can stimulate bloom initiation by the luminescent counterparts and the subsequent gradual shift of grazing community from the regions of bloom formation is thought to facilitate bloom persistence. Toxicity of bloom-forming dinoflagellates can also serve as a grazing deterrent and a bloom initiation factor by alleviating grazing pressure on them²⁵. In Indian waters, reduced abundance of diatoms and higher trophic level organisms, such as copepods and pelagic fishes, have been documented during dinoflagellate blooms on multiple occasions^{26,27}. Apart from the recognised environmental factors that contribute to reduced grazing during bloom events, the relationship between these observations and the bioluminescence displayed by dinoflagellates requires further investigation. Along the Indian coastal waters, bioluminescence blooms of a toxic dinoflagellate, *Gonyaulax spinifera* (Claparède & Lachmann) Diesing, 1866 have been recorded during March 2020^(ref. 28) with no apparent harmful impact on human health and marine organisms. However, thorough consideration is required for the potential influence of bioluminescence and toxicity in hastening bloom episodes, given the genetic variability observed in natural bloom populations for both bioluminescence and toxin production¹⁵.

A comprehensive examination of bioluminescence blooms and associated species is essential. Apart from the visual appeal, the presence and persistence of bioluminescent blooms of dinoflagellates result in various detrimental effects on marine biodiversity,

human health, and the economy, akin to other types of bloom events. Along the Indian coasts, of the 26 reports on bioluminescence blooms, a large majority of 16 bloom episodes were caused by dinoflagellates, primarily dominated by *N. scintillans*. Massive outbreaks of *N. scintillans* can disrupt the conventional food chain supported by diatoms as they are not the favoured dietary source for copepods and other mesozooplankton²⁹. These blooms can lead to significant degradation of the aquatic life marked by increased mortality rates of fishes, crustaceans, and other marine fauna and flora due to depletion of dissolved oxygen in sea water³⁰⁻³². Increasing fish mortality rates affects the fishing industry and livelihood of fishermen³³. It can also result in a significant increase in fish prices, affecting human consumption. The blooms also cause the destruction of coral reefs and associated biodiversity due to O₂ depletion, non-availability of nutrients and light, degeneration of seaweeds²⁷, and respiratory irritations for humans³⁴. Biomagnification of potent neurotoxins from bloom-forming algal species through fishes and shellfish to humans is also reported to cause several neurological and gastrointestinal diseases³⁵. The

world tourism industry and associated recreational activities are also adversely affected by HAB events, and some of them are often caused by bioluminescent dinoflagellates³⁶. In India, tourism is a prime source of revenue, and outbreaks of highly toxic HABs can lead to the closure of beaches to avoid possible health issues. The spread of foul odour from HABs due to the decomposition of dead algae can cause severe discomfort for the general public. The persistence of HAB can clog the filters and membranes of coastal power plants, causing severe economic loss. Systematic monitoring of these blooms, their modelling as well as forecasting is essential for human health, economy, and for the protection and safeguarding of aquatic life.

Multiple natural and anthropogenic factors contribute to the occurrence of dinoflagellate bloom events (Fig. 4). Seasonal fluctuations in environmental conditions like water temperature, dissolved oxygen, nutrient levels, cold eddies, and stoichiometry influence phytoplankton growth. For instance, variations in rainfall, wind direction, eddies, convective mixing, and upwelling in the Arabian Sea exert an indirect influence on HAB events^{29,37}.

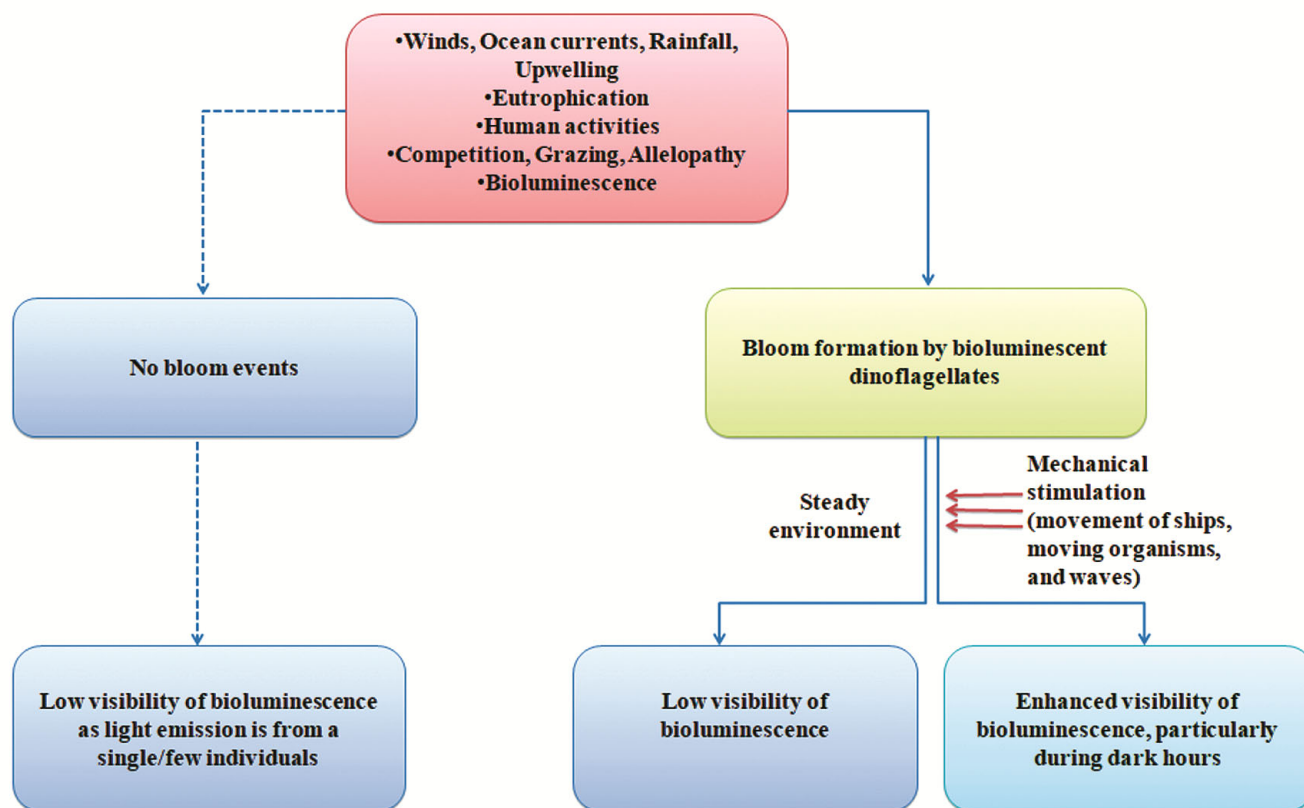


Fig. 4 — Schematic representation of bioluminescence bloom formation by dinoflagellates

Eutrophication is the prime factor causing HABs in the global water bodies, and its sources can be either natural or anthropogenic. Among the major sources of nutrients include dust deposition, seabed, and human activities^{38,39}. Increased human activities, drying marshlands, and construction works, have increased HAB occurrences⁴⁰. The release of high-temperature industrial wastewater from coastal power plants into the seas increases nutrient concentration, causing HAB outbreaks. High water temperature can also affect the rate of photosynthesis, CO₂ fixation, the chemical composition of the phytoplankton cells, and growth rates^{41,42}.

The literature review highlights that environmental drivers of dinoflagellate bloom events have garnered considerable global and national attention. However, the potential factors influencing bioluminescence blooms, including genetic variability in light emission and the quantification of bioluminescence intensity, remain to be fully understood.

Marine bioluminescence studies in India – How far have we come?

Bioluminescence blooms have been observed along the inshore and offshore waters of India since decades ago. A detailed review of the luminescent terrestrial and marine organisms of India is given by Chatragadda⁴³; bioluminescence bloom occurrences of *Thalassicolla* sp., *P. granii*, *Peridinium* sp., *Pyrocystis* sp., and *N. scintillans* have also been reviewed. Since the occurrence of luminescent blue glows of a radiolarian, *Thalassicolla* sp., off the Andaman Islands⁴⁴, several studies have reported bioluminescence observation along the Indian waters (Table 1). The bioluminescent blooms were dominated by dinoflagellates followed by ostracods. Within the northern Arabian Sea, a notable occurrence involved the bioluminescent swarming of the ostracod *C. dentata*, primarily for mating⁴⁵. Additionally, temporal monitoring of plankton groups associated with *V. hilgendorffii* bioluminescence was reported from the Kavaratti Lagoon of Lakshadweep Islands⁴⁶. Though huge attention has been received on the occurrence of luminescent glows and the causative species, research attempts to decipher the bioluminescent properties of these blooming species from India are still in its infancy. However, in recent times, substantial efforts have been directed towards the *in situ* quantification of bioluminescence of dinoflagellates²⁸, to understand their response to

various mechanical stimuli, as well as its diurnal variations, photo-inhibition and circadian rhythms⁴⁷.

Applications and future research issues

Globally, bioluminescence has been routinely used in toxicity assays, immunoassays, bio-imaging, drug discovery, gene expression studies, protein-protein interactions, disease progression, mapping of metabolic processes, and blue-sky researches⁴⁸⁻⁵⁰. In Indian scenario, applications of marine bioluminescence are largely limited to bacterial bioluminescence. Attempts have been made to delineate the role of marine bacterial bioluminescence in ecological functions⁵¹, toxicity bioassays⁵²⁻⁵⁴, environmental radiotoxicity sensing⁵⁵, marine pharmaceutical applications⁵⁶, and industrial applications⁵⁷. Research has been undertaken to investigate the luminescent bacterial disease and its impacts on aquaculture⁵⁸. More recently, an Indian company – Rexofa Food Technology – has used the enzyme derived from *Aequorea* to develop bioluminescence lollipops and ice-cream that will glow green colour⁵⁹. However, studies on other marine bioluminescent groups are still lacking from India, and thorough investigations on the diversity and distribution of bioluminescence, chemistry of light emission, genes regulating light emission and luciferin synthesis, bioluminescence response to various stimuli, and regional/diurnal variations in bioluminescence potential are substantial to provide baseline data for developing future applications. The ecological significance of bioluminescent glows also requires extensive studies.

From the available literature, dinoflagellates are the most often encountered bloom-forming luminescent organisms along the Indian waters. Bioluminescence potential of dinoflagellates, the primary source of marine bioluminescence in surface waters, is largely explored on a global scale. Dinoflagellates such as *Pyrocystis lunula*, *Lingulodinium polyedrum*, *Ceratocorys horrida* and *Pyrocystis noctiluca* have been extensively used in environmental bioassays (e.g.: QwikLite™) to evaluate the toxicity of contaminants in marine environments^{49,60}. Dinoflagellate bioluminescence has also been employed to characterise bioreactor processes⁶¹, detecting underwater targets and in military applications²². Further, dinoflagellate luciferase has been employed in measuring the expression of cell surface-membrane protein⁶². New horizons in the application of dinoflagellates bioluminescence include the

development of luminous toys (e.g. DinoPet and Bio-Orb) and interactive art installations (e.g. Glowing Nature from Studio Roosegaarde). Recently, polymersome nanoreactors that are responsive to shear stress have been developed, inspired by the concept of mechanosensing events that lead to bioluminescence in dinoflagellates upon receiving hydrodynamic turbulences⁶³. Nevertheless, studies on dinoflagellate bioluminescence face certain limitations stemming from challenges in maintaining their laboratory cultures and conflicting reports regarding their bioluminescence capabilities. However, in-depth investigations on dinoflagellates bioluminescence are imperative. A thorough understanding of the mechanism of light emission in dinoflagellates and the intermediate molecule formed can greatly stretch their applications in biotechnology and environmental sciences⁶⁴.

Conclusions

In summary, from the literature survey, it is evident that although bioluminescent blooms are a prevalent phenomenon along the coastal waters of India, it remains largely understudied. Bioluminescence, though very picturesque, might facilitate the persistence of HABs affecting biodiversity and the national economy. More *in situ* measurements of bioluminescence intensity and associated hydrographical variables can be of great help in forecasting future bioluminescence and its exact pre-conditioning factors, thereby reducing the possible impacts. The repeated occurrences of marine bioluminescence and its relationship with different facets of climate change (mainly ocean acidification and ocean warming) demands thorough future research efforts. This includes the development of improved and robust automated technologies for detecting marine bioluminescence.

Bioluminescence can serve as a predictive tool for harmful algal blooms and may also be considered as an indicator of the plankton biomass. Thorough studies on the diversity and distribution of bioluminescent biota, as well as the intensity and the functional and adaptive significance of their light emission, are also equally in demand. Targeted monitoring programs involving citizen science approach should be promoted in periodic assessment of bioluminescence events.

Acknowledgements

The authors are grateful to the Director, Zoological Survey of India, and to the Department of Science and Technology (Project: ECR/2017/000087 and

CRG/2020/005212) for providing amenities to carry out this work. We are also thankful to UGC for providing SRF fellowship to Haritha Prasad [Ref. No.: 983/(CSIR-UGC NET JUNE 2019)], and to CSIR for providing SRF fellowship to Alfisa Siddique (sanction letter number 09/1181(0003)/2017-EMR-I).

Conflict of Interest

The authors declare no conflicts of interest in any of the materials discussed in this article.

Ethical Statement

Human subjects or animals were not involved in this study.

Author Contributions

HP: Conceptualization and writing-original draft; AS: Writing-original draft; JP: Supervision, writing-review & editing, resources; and CR: Resources.

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