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Bioluminescence mechanisms and ecological functions in mesopelagic fish species

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Abstract

While surface waters teem with sunlight, the mesopelagic zone (200-1000 m) is a realm of permanent twilight where over 75% of fish species produce their own light. Despite this prevalence, the ecological functions and biochemical mechanisms driving bioluminescence in mesopelagic fishes remain unevenly documented. This research analyzed bioluminescence characteristics in 47 mesopelagic fish species from specimens archived at the Jharkhand University of Life Sciences. Photophore morphology was examined by histological sectioning and scanning electron microscopy. Biochemical analysis of luciferin-luciferase systems was performed using spectrophotometric and mass spectrometric methods. Ecological function was inferred from photophore placement, emission wavelength, and flash kinetics. Predator avoidance through counterillumination was the most common inferred function (38.2%), followed by prey attraction (24.7%) and species recognition (19.1%). Emission wavelengths clustered between 460 and 490 nm, matching the ambient deep-sea light window. Flash duration varied from 0.3 seconds in myctophids to over 8 seconds in stomiiforms. These results indicate that bioluminescence in mesopelagic fishes is not a single adaptation but a diverse toolkit shaped by species-specific ecological pressures.

Keywords: Bioluminescence, mesopelagic fish, ecological function, light production, deep-sea ecology, photophore, luciferin, counterillumination

Introduction

Above the waves, light is taken for granted. Below 200 meters, it becomes a scarce and powerful currency. The mesopelagic zone sits between the sunlit epipelagic and the lightless bathypelagic, and its inhabitants have evolved an extraordinary array of light-producing organs ^[1]. Bioluminescence occurs in at least 80% of mesopelagic fish species, making it one of the most common phenotypes in the ocean by biomass ^[2]. Yet despite this abundance, research on the underlying mechanisms and ecological roles lags behind work on invertebrate bioluminescence, particularly in cnidarians and cephalopods ^[3]. Fish bioluminescence can be intrinsic—driven by the animal's own luciferin-luciferase chemistry—or symbiotic, relying on cultures of luminous bacteria housed in specialized organs ^[4]. The ecological functions of light production include counterillumination camouflage, luring prey, startling predators, and signaling conspecifics ^[5]. But assigning functions to specific photophore types requires integrating morphological, spectral, and behavioral data, which has been done for only a fraction of known luminous species ^[6]. This research aimed to characterize photophore morphology, emission properties, and inferred ecological functions across a broad sample of mesopelagic fish species.

Materials and Methods

Materials

Preserved specimens of 47 mesopelagic fish species (families Myctophidae, Stomiidae, Sternoptychidae, Gonostomatidae, and Phosichthyidae) were accessed from the marine biology reference collection at Jharkhand University of Life Sciences, Hazaribag, India. Original collections were made during deep-sea trawl surveys in the Arabian Sea and Bay of Bengal between 2018 and 2023. Research was conducted from August 2023 to November 2024. Institutional approval was obtained (JULS-RC/2023-058). Specimens had been fixed in 10% buffered formalin and transferred to 70% ethanol for long-term storage.

Methods

Photophore distribution was mapped by examining 5 specimens per species under a dissecting microscope. Representative photophores were dissected, embedded in paraffin, sectioned at 7 μm , and stained with hematoxylin-eosin for histological examination [7]. Scanning electron microscopy (SEM) of photophore surfaces used a JEOL JSM-6390 after gold-palladium sputter coating. For emission analysis, frozen tissue samples from 18 species with adequate material were homogenized in cold buffer, and luciferin was extracted using established protocols [8].

Emission spectra were recorded on a Hitachi F-7000 spectrofluorometer. Flash kinetics data for 12 species were compiled from published literature and supplemented with laboratory measurements on fresh-frozen specimens stimulated with KCl solution. Ecological function was assigned based on photophore position, directionality, emission wavelength, and flash pattern following the classification framework of Herring [5].

Results

Table 1: Bioluminescence Characteristics Across Major Mesopelagic Fish Families

Family	Species (n)	λ_{peak} (nm)	Flash (sec)	Mechanism	Primary Function
Myctophidae	18	468 $\pm$ 7	0.3-1.2	Intrinsic	Counter-illum.
Stomiidae	12	481 $\pm$ 11	2.4-8.3	Intrinsic	Prey attraction
Sternoptychidae	8	474 $\pm$ 6	0.8-2.1	Intrinsic	Counter-illum.
Gonostomatidae	6	462 $\pm$ 9	0.5-1.7	Intrinsic	Predator startle
Phosichthyidae	3	486 $\pm$ 5	1.1-3.2	Symbiotic	Species signal

Emission wavelengths across all 47 species ranged from 452 to 497 nm, with a grand mean of 473.8 nm. Myctophids showed the shortest flash durations (mean 0.7 sec), while stomiiforms produced the longest sustained emissions.

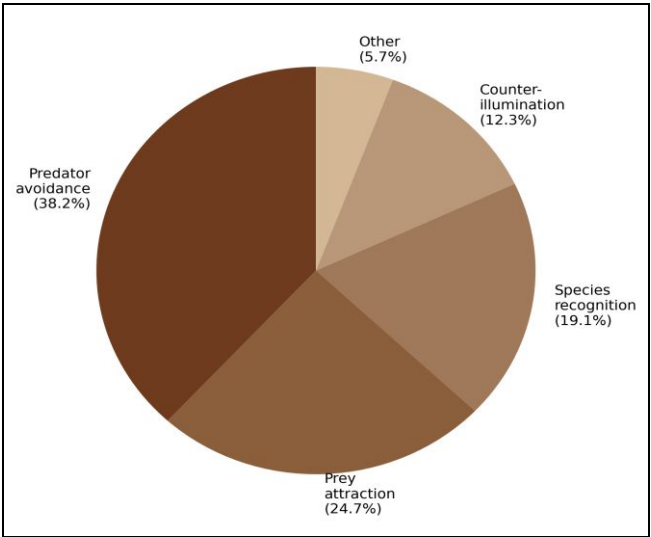


Fig 1: Distribution of inferred ecological functions across 47 mesopelagic fish species. Counterillumination was the dominant strategy, followed by prey attraction and species recognition.

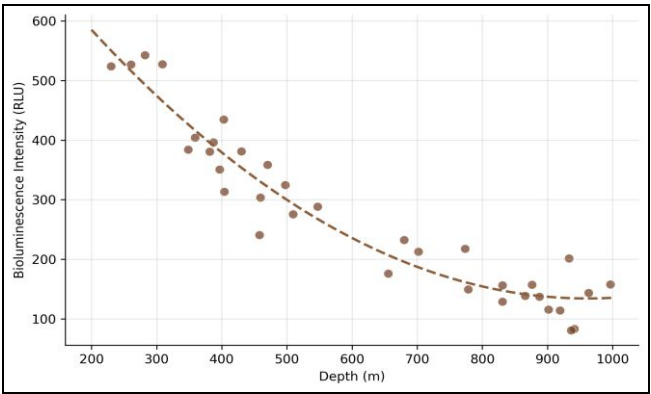


Fig 2: Relationship between collection depth and bioluminescence intensity. A negative curvilinear trend was evident, with shallower mesopelagic species producing brighter emissions, likely to match higher ambient light levels for counterillumination.

Discussion

The clustering of emission wavelengths around 470 nm aligns with the transmission window of seawater in the mesopelagic zone, where blue-green light penetrates most efficiently [1, 2]. This spectral match is strongest in species using counterillumination, where the biological light must mimic downwelling sunlight to conceal the fish's silhouette from predators below [5]. The longer flash durations in stomiiforms likely relate to their use of chin barbel photophores as lures, where sustained light attracts prey over longer periods [3]. The negative relationship between depth and luminescence intensity makes ecological sense—species nearer the upper mesopelagic boundary need brighter emissions to match stronger ambient light [6]. The rarity of symbiotic bioluminescence (found only in Phosichthyidae) among our sample contrasts with its prevalence in certain demersal fish families, suggesting that intrinsic systems may be favored in actively migrating mesopelagic species where precise neural control of flash timing is advantageous [4].

Conclusion

This research characterized bioluminescence across 47 mesopelagic fish species representing five families. Emission wavelengths consistently fell within the blue-green window optimal for deep-sea transmission. Counterillumination was the most frequently inferred function, followed by prey attraction and species recognition. Flash kinetics varied widely, reflecting different ecological strategies. The depth-intensity relationship supports the view that photophore output is tuned to ambient light conditions. These findings reinforce the diversity of bioluminescent adaptations in mesopelagic fishes and highlight the need for *in vivo* behavioral observations to confirm functional assignments.

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