New observations of fluorescent organisms in the Banda Sea and in the Red Sea

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Abstract

Fluorescence is a widespread phenomenon found in animals, bacteria, fungi, and plants. In marine environments fluorescence has been proposed to play a role in physiological and behavioral responses. Fluorescence has been described in jellyfish, corals and fish, and many fluorescent proteins and molecules have been identified. Here we describe new fluorescent species, which we found during night dives in the Banda Sea, Indonesia, and in the Red Sea, Egypt. Among various phyla we found fluorescence in sponges, molluscs, tunicates, and fish and, with this, extend the knowledge on the number of fluorescent species in marine environments.

Keywords: Fluorescence, marine organsims, coral reefs, Banda Islands, Red Sea

33 **Introduction**

34 Fluorescence is the property of a molecule to absorb light of a certain wavelength followed by
35 the emission of light with longer wavelength. In bacteria, plants, fungi and animals, various
36 fluorescent molecules have been described such as chitin, minerals, carotenoids, flavonoids,
37 porphyrins, chlorophyll, phycobiliproteins or green fluorescent protein (GFP)-like fluorescent
38 proteins. These molecules can be excited by either sun- or moonlight [1,2].

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40 In marine environments many fluorescent species have been described and for various of
41 these species an ecological and/or physiological function has been suggested. Only a few
42 studies addressed the behavioral and physiological role of fluorescence [2]. In jellyfish, for
43 example, where the first fluorescent protein (avGFP) was characterized, GFP is expressed as
44 an acceptor molecule for bioluminescent light in its tentacles [3]. The green fluorescence is
45 used to attract prey [4]. So far fluorescent proteins have been found in Cnidaria, Vertebrata,
46 Cephalochordata (lancelets) and Arthropoda, but have not been described in Porifera
47 (sponges), Ctenophora (comb jellies), Tunicata (tunicates), Hemichordata (hemichordates),
48 Echinodermata (echinoderms), Mollusca (molluscs), Annelida (segmented worms) and
49 Nematoda (roundworms) [5–7]. Most fluorescent proteins with blue to red emission spectra
50 have been identified in Anthozoa (corals). Here the fluorescence has been shown to be
51 involved in attraction of photosynthetic symbionts, in photoprotection of the symbionts and in
52 converting blue light to longer wavelength light in mesophotic environments
53 (photoenhancement) [2]. Note that the green to red components of the sunlight are selectively
54 removed with water depth resulting in a blue light environment [8]. In fish red fluorescent body
55 coloration and red fluorescent eye rings have been shown to be involved in intra- and
56 interspecific communication [9–13]. In addition, differences in the fluorescence pattern
57 between males and females have been suggested to play a role in sexual communication
58 [10,14].

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In contrast to jellyfish, corals, sea anemones, deep-sea benthic copepods, lancelets, eels and moray eels, where fluorescence is based on the expression of fluorescent proteins, non-FP based fluorescence has been observed in Porifera (sponges), Heterobranchia (slugs and snails), Annelida (segmented worms), Crustacea (copepods), Osteichthyes (bony fish) and Chondrichthyes (cartilaginous fishes) [8,15–19]. For most species, excluding jellyfish, corals and fish, the physiological function of fluorescence and the fluorescent molecules have not been identified.

Here we describe several new fluorescent species, which we found during night dives in the Banda Sea, Banda Islands, Indonesia and the Red Sea, Dahab, Egypt. These new fluorescent species include nudibranchs, tunicates, sponges, various other invertebrates, and fish. In addition to the new species, we show detailed images of known fluorescent species to give precise information about the distribution of body fluorescence.

Methods

Photo acquisition in the field

Images of new fluorescent species were acquired during SCUBA diving in the Red Sea in Dahab, Egypt (28°29’20.0”N 34°30’57.2”E) and in the Banda Sea at the Banda Islands, Maluku, Indonesia (4°30’55.62”S 129°53’35.92”E). All dives were started after sunset and limited to a maximum depth of 15 meters, which was monitored by a dive computer. Field observations were carried out in May 2019 (Red Sea) and in February-March 2019 and September 2022 (Indo Pacific).

Fluorescence was excited with “Sola” light source (NightSea, USA; ʎ max = 449 nm), Flashlight (D2000; INON; Japan), Ex-Inon excitation filter (NightSea, USA; ʎ max = 454 nm) or “Blue Star” light source (NightSea, USA; ʎ max = 470 nm). The transmission filter (BF 2, NightSea, USA) in front of the underwater housing showed a low cut at ʎ < 500 nm. Fluorescence photography was performed with Powershot G15 (Canon, Japan) placed in WP DC 48 (Canon, Japan) underwater housing or Sony α 6000 (Sony, Japan) placed in SF-A6500 (Seafrogs, Hongkong) underwater housing. All images were processed with Lightroom (Version 2015.1.1, Adobe, USA) and Corel Draw (Version 20.0.0.633, Corel Corporation, Canada), by correcting the brightness, contrast, removing haze and cropping the images.

Species were identified with standard literature [20–29]. The species were identified by comparison of digital underwater pictures with the description and pictures of the literature. Since we did not take DNA or tissue samples, the species information must be interpreted with caution for the less distinct taxa.

Photo acquisition by Leica Thunder

Detailed images of *Anampses meleagrides* [Randall, 1972], *Cirrhilabrus aquamarines* [Tea, 2021], *Cirrhilabrus rubrisquamis* [Randall & Emery, 1983], *Doryrhamphus excisus* [Kaup, 1856], *Eviota atriventris* [Greenfield & Suzuki 2012], *Eviota nigriventris* [Giltay 1933],

Lybia tessellata [Latreille in Milbert, 1812], *Nembrotha kubaryana* [Bergh, 1877], *Odontodactylus scyllarus* [Linnaeus, 1758], one species of Polyplacophora, *Synchiropus sycorax* [Tea & Gill, 2016], were acquired with the fluorescence stereoscope Leica M205 FCA equipped with a DFC90000 GT Camera and a GFP (λ_{Ex}: 395–455 nm, λ_{Em}: 480 LP), mCherry (λ_{Ex}: 540-580 nm, λ_{Em}: 593-667 nm) and a CY5 (λ_{Ex}: 590–650 nm, λ_{Em}: 663–737 nm) filter cube. The fish and invertebrates were purchased from the wholesale trader DeJong Marinelife (Netherlands) in 2021/2022 or from Korallenfarm Joe & Co (Germany). All images were processed with LASX (Version 3.7.6.25997, Leica, Germay), Lightroom (Version 2015.1.1, Adobe, USA) and Corel Draw (Version 20.0.0.633, Corel Corporation, Canada) by correcting and/or cropping the images.

Results

During night dives at the Banda Islands, Indonesia and Dahab, Egypt new fluorescent species belonging to the phyla Porifera, Mollusca, Arthropoda, Annelida and Chordata could be identified.

Porifera - We found green, yellow and orange fluorescence in different unidentified sponges in Egypt (Fig. 1 C) and in Indonesia (Fig. 1 D). *Gelliodes fibulata* [Ridley, 1884] revealed green fluorescent spots on its surface (Fig. 1 A, B).

Corals – We found a variety of shallow-water stony corals that exhibited yellow fluorescence (Fig. 2), namely *Physogyra lichensteini* [Milne Edwards & Haime, 1851], three different species of *Montipora* and two *Fungia* species.

Molluscs - In molluscs we found fluorescence in the families Octopodidae, Strombidae, Cardiidae, Facelinidae (Fig. 3), Polyceridae (Fig. 4) and unidentified families of Polyplacophora (Fig. 5). The octopus *Abdopus aculeatus* [Férussac & d'Orbigny], 1834] revealed orange fluorescent areas on its body. Bright fluorescent patches were located below the yellow fluorescent eyes and on every arm (Fig. 3 A & B). Other species (unspecified) of the same family showed no fluorescence, but had yellow fluorescent eyes, most likely representing yellow intraocular filters (Fig. 3 B, D, E). We found green and red fluorescence in several snails. The bubble conch *Euprotomus bulla* [Röding, 1798] had a bright green fluorescent operculum and weak green fluorescent eyes. The giant clam *Tridacna crocea* [Lamarck, 1819] showed a very bright red fluorescence that could be related to photosynthetic symbiotic algae (Fig. 3 G). In addition, the nudibranch *Facelina rhodopos* [Yonow, 2000] (Fig. 3 H) showed bright orange fluorescence at the tip of the cerata, which most likely was related to ingested metabolites of the prey-hydrozoan *Millepora sp*.. Another nudibranch *Nembrotha kubaryana* that we found in the Banda Sea in its natural habitat (Fig. 4 A), and had purchased from Dejong Marinelife (Netherlands) revealed strong red fluorescence (Fig. 4 B). We were able to localize the

fluorescence in more detail under laboratory settings and found fluorescent patches around the mouth (Fig. 4 D), the rhinophores (Fig. 4 E - G), gills (Fig. 4 B) and the dorsal rim (Fig. 4 B & H). We also found a variety of different Polyplacophora that exhibited bright green, yellow and red fluorescence (Fig. 5 A - D).

Echinodermata – We found bright green, yellow and red fluorescent crinoid species of different genera at the Banda Islands and in the Red Sea (Figure 6).

Arthropoda - Several fluorescent decapoda of the family Inachidae, Scyllaridae and Palaemonidae were found. The decorator crab *Camposcia retusa* [Latreille, 1829] (Fig. 7 A Banda Sea) showed a bright green fluorescent carapace. In the Red Sea we discovered a bright green fluorescing slipper lobster *Scyllarides sp*. (Fig. 7 B). In addition, we found bright green fluorescence in the carapace of Coleman`s Shrimp*, Periclimenes colemani* [Bruce, 1975] (Fig. 7 C), living in symbiosis with fire urchins that do not fluoresce. Green and red fluorescence of the carapace was discovered in peacock mantis shrimps *Odontodactylus scyllarus*. The images revealed fluorescence in filamentous structures on pleopods (Fig. 8 C), uropods (Fig. 8 E), paraeopods (Fig. 8 D), and on maxillipeds (Fig. 8 A, B, F). Furthermore, we identified fluorescent body parts of the Mosaic Boxer Crab (*Lybia tessellata*) (Fig. 8 G)

Annelida - We also found fluorescence in two types of bristle worms (polychaetes) from the family Eunicidae and Sabellidae. In the subclass Eunicida only the bristles fluoresced bright green (Fig. 7 D, F). In addition, we found bright yellow fluorescence in a feather duster worm (Sabellidae) (Fig. 7 E).

Chordata – Two fluorescent tunicate species and three new species of fluorescent bony fish were photographed in the Banda Sea, Indonesia. Both tunicates, the ascidians *Clavelina coerulea* [Oka, 1934] (Fig. 9 A & B) and *Clavelina robusta* [Kott, 1990] (Fig.9 C & D)

revealed a bright green rim-like fluorescence around their siphons. In both species the fluorescent rims appeared yellow under white light conditions. We found two green and orange fluorescent scarlet frogfish *Antennatus coccineus* [Lesson, 1831] (Fig. 6 A & B). The green fluorescence was distributed over the entire body, while the orange fluorescence was found in patches and in the lures. In addition, we found a bright fluorescing green leopard flounder *Bothus pantherinus* [Rüppell, 1830] (Fig. 10 C). Green fluorescence was more prominent in the white banded parts of the skin. We also found individual differences in fluorescence in the banded pipefish *Corythoichthys intestinalis* [Ramsay, 1881]. Individuals revealed either green or orange fluorescent skin patterns (Fig. 10 D-F). However, all individuals revealed a bright yellow/orange fluorescence around the eyes and the caudal fin (Fig. 10 D-F). Moreover, we observed two individuals of *Pleurosicya mossambica* [Smith, 1959] in the Banda Sea with bright orange-red fluorescence around the eyes and the chorda (Fig. 11 A & B) and two individuals of *Scorpaenopsis possi* [Randall & Eschmeyer, 2002] with orange and red fluorescent patches in their tissue (Fig. 11 C & D). In addition, we found two different color morphs of *Soleichthys heterorhinos* [Bleeker, 1856] from the Banda Sea (E) and Red Sea (F) and a green fluorescent undefined species of Lutjanidae (G), and *Brachysomophis henshawi* [Jordan & Snyder, 1904] with a red fluorescent head (H). Detailed microscope images of green and red fluorescent fish are provided in Figure 12 and 13.

Discussion

During night dives in the Banda Sea, Indonesia and the Red Sea, Egypt we photographed marine organisms, in which, to our knowledge, fluorescence had not been described before. These include sponges, crustaceans, polychaetes, slugs, snails, octopus, ascidians, and fish.

Fluorescence has been described in various marine organisms and many behavioural and physiological functions have been suggested. Only a few studies were conducted, which show a correlation between fluorescence and visual guided behaviour or physiological responses [2]. We will, therefore, relate these functions to the new fluorescent species we found:

Fluorescence in sponges has been described in a few species, and it was suggested that fluorescence might be used for photoenhancement, i.e. the conversion of blue light into longer wavelength light. Photoenhancement has been discussed in mesophotic environments. Since yellow green fluorescent sponges can be found at depths of up to 40 m [16], and fluorescence is expressed in archaeocytes [15], which ingest and digest food, the fluorescence might be used to attract prey. Wether the green fluorescent spots we observed for *Gelliodes fibulata* are intrinsic to the sponge or are secondary to some symbionts or parasites needs to be investigated.

To date, fluorescence has been described and characterized mainly in corals and many FPs have been identified. Yellow to red fluorescent corals are usually found in the mesophotic coral ecosystem, where fluorescence most likely plays a role in photoenhancement [30,31]. It was therefore surprising that we found various yellow fluorescent corals in the shallow reefs (<10m) in Egypt and Indonesia.

Several crustaceans have been described to be fluorescent [32–35], where fluorescence was shown to be produced by autofluorescence. This could also be the case for the green fluorescing cuticula of the slipper lobster (Fig. 4 B). Symbionts (fluorescent microalgae), or

213 fluorescent molecules such as chitin, lipofuscin, or tryptophan associated molecules could
214 cause the fluorescence here [2]. For isopods that live in symbiosis with red fluorescent
215 microbes, it has been suggested that the red fluorescence might serve as a warning signal for
216 predators [19]. Pontellidae, a family of copepods show sexual dimorphism in eye design with
217 different fluorescent patterns [33,35,36]. It has also been suggested that the different patterns
218 might be involved in intraspecific recognition. In addition, countershading has been suggested
219 for blue and green fluorescence [35]. This could also be the case for the decorator crab (Fig.
220 4 A) and the Coleman`s Shrimp (Fig. 4 C). Whether fluorescence is also used for
221 communication in the newly discovered fluorescent species, similar to the mantis shrimp [37],
222 or it is an unfunctional epiphenomenon [38], still needs to be investigated.
223
224 Fluorescence has also been described in various segmented worms. The intertidal worm
225 *Eulalia sp.* (Polychaeta) secretes a blue-green fluorescent mucus, which has been suggested
226 to protect the worm against high-energy radiation. The gossamer worm (*Tomopteris spp., a*
227 pelagic annelid) uses fluorescence to enhance bioluminescent light [39]. In the tubeworm
228 *Chaetopterus variopedatus* the mucus of the worm contains blue and green fluorescence
229 mediated by riboflavin and related derivatives [2,40,41]. In addition, blue fluorescence and
230 bioluminescence has also been observed in the fireworm *Odontosyllis phosphorea* [42,43].
231 While the fluorescent molecules are most likely used to enhance light spectra within the
232 luminescent worms, a physiological/behavioral function has not been demonstrated [2]. We
233 also found fluorescence in fire or bristle worms from the family Eunicidae and Sabellidae with
234 so far unknown function (Fig. 4 D-F).
235
236 Fluorescence is known from molluscs [17] . The giant clams *Tridacna* (Fig. 2 G) and *Hippopus*
237 live in symbiosis with red fluorescent photosynthetic algae, which are hosted in the mantle
238 tissue. The fluorescence seen for *Tridacna* is therefore most likely associated to the chlorophyll
239 photosystem II of the algae [44–46]. In snails fluorescence is often found in the cerata, which
240 originate either from ingested food (green fluorescence) or symbiotic algae (red) [17]. It could

be possible, that the Nudibranch *Facelina rhodopos* deposits ingested fluorescent food in their cerata since this snail feeds on the hydrozoan *Millepora,* that has a weak fluorescence. Behavioural experiments with *Goniobranchus splendidus* revealed that predators learn to avoid feeding on the unpalatable snail. The avoidance behaviour of the fish is triggered by the yellow rim of the snail [47]. These experiments suggest that the red fluorescent rim of *Nebrotha kubaryana* may be an aposematic signal.

In Cephalopoda fluorescence had not been described so far. It is therefore surprising to find green and red fluorescence in the octopus *Abdopus aculeatus*. Based on the distribution and pattern of the fluorescence one could speculate that fluorescence is involved in intraspecific communication.

Another surprising result was the occurrence of fluorescence in two species of ascidians. In both species bright green fluorescence was seen in a rim-like structure around the oral and atrial siphon (Fig. 5). Since food is ingested via the oral siphon, fluorescence might be involved in attraction of plankton which was demonstrated for the green fluorescence of the jellyfish *Olindias formosa* [4]. A similar function of fluorescence might also play a role in the green to red fluorescence of echinoderms.

Green and red fluorescence is common in fish. In crypto-benthic fish, such as the Scarlet frogfish and the Leopard flounder (Figure 10) fluorescence may facilitate background matching (camouflage) [8,48]. Red fluorescent body coloration in the red-eyed wrasse *Cirrhilabrus solorensis* has been shown to increase aggressive behavior by increased recognition of fluorescent possible rivals and might also be involved in sexual communication based on the difference in the fluorescence pattern between males and females [9,10,14]. Red fluorescent eye rings in the black-faced blenny *Tripterygion delaisi* are most likely used for intraspecific communication since the fish can perceive and respond to red fluorescence [11–

13]. Thus, the red fluorescent eye rings we observed in the pipefish may play a similar role for short distance communication.

This study contributes twenty one new species to the database of known fluorescent marine organisms. Three of these species belonged to the phylum Porifera, seven to the phylum Mollusca, three to the subphylum Crustacea, three to the phylum of Annelida, two to the class Ascidiacea and three to the subphylum Vertebrata. We describe for the first-time fluorescence in Octopoda and Ascidiacea, and also show the first case of fluorescence in Nudibranchia, where the fluorescence is not linked to ingested food. This study, therefore, extends the palette of fluorescent marine species.

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Competing interests

The authors declare that they have no competing interests.

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Availability of data and material

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Authors' contributions

Conceptualization LHP, MH, SH

Investigation LHP, BS, GL

Writing – Original LHP, BS, GL, MH, SH

Writing – Review & Editing LHP, MH, SH

Figures

Figure 1: Fluorescence in Porifera in the Banda Sea: The thorny stem sponge *Gelliodes fibulata* ((A & B) white light in A, fluorescence in B) show green fluorescent spots over the whole tissue. Two unidentified sponges (C, D) fluoresce yellow and green.

Figure 2: Fluorescence in corals: Yellow fluorescent corals in the Banda Sea and in the Red Sea. *Physogyra lichensteinii* (A), *Montipora sp.* (B - D) and *Cycloseris* sp./*Fungia sp.* (E & F). A, B, D - F: Banda Sea, C: Red Sea.

Figure 3: Fluorescence in Mollusca: Three different types of fluorescent Octopods; *Abdopus aculeatus* (A & B) with orange fluorescent parts of skin, two unidentified species of Octopodidae (C – E) with fluorescent eyes, green fluorescent operculum of *Euprotomus bulla* (F), red fluorescent mantle of *Tridacna crocea* (G), orange fluorescent *Facelina rhodopus* (H) on *Millepora sp*.. A – G: Banda Sea, H: Red Sea

Figure 4: Fluorescence in the nudibranch *Nebrotha kubaryana:* (A) natural habitat (Banda Sea), white light & Fluorescence (B), whole body (B, C), oral tentacles (D), rhinophores (E-G), gill (H) fluorescence. Pictures C – H created with a Thunder microscope (Leica, Germany) with CY5 filter.

Figure 5: Polyplacophora: Red, yellow and green fluorescent Polyplacophora in the Red Sea (A-C) and in the Banda Sea (D). Bright green and red fluorescent Polyplacophora in a reef tank in E-F.

Figure 6: Fluorescence in Echinoderms: New observations of red, yellow and green fluorescence in crinoids from the Banda Sea (A-E) and in the Red Sea (F-H).

Figure 7: Fluorescence in Arthropoda and Annelida: Green fluorescent *Camposcia retusa* (A), *Scyllarides sp. (B)*, *Periclimenes colemani* (C), Eunicida (D,F), Yellow fluorescent chaeta of an unidentified species of Sabellidae (E). A, C, D, F: Banda Sea, B & E: Red Sea

Figure 8: Fluorescence of *Odontodactylus scyllarus* and *Lybia tessellata:* Green (GFP filter) and red fluorescing (Cy5 filter) structures of maxillipeds (A, B, F), pleopods (C), uropods (E) and paraeopods (D). Green and red fluorescing *Lybia tessellata* (G; GFP & CY5 filter). Pictures were taken on a Thunder microscope (Leica, Germany).

Figure 9: Fluorescence in Tunicata in the Banda Sea: White light and fluorescent picture of *Clavelina coerulea* (A, B), *Clavelina robusta* (C,D). The green fluorescence concentrates on the siphons of the ascidians.

Figure 10: Fluorescence in fish in the Banda Sea: Green and orange fluorescing *Antennatus coccineus* (A,B), green fluorescing *Bothus pantherinus* (C) and different fluorescing individuals of *Corythoichthys intestinalis* (D-F).

Figure 11 Fluorescence in fish: Red fluorescing *Pleurosicya mossambica* (A & B), *Scorpaenopsis possi* (C & D), different colormorphs of orange fluorescing *Soleichthys heterorhinos* (E & F), undefined species of Lutjanidae (G) and *Brachysomophis henshawi* (H) with a red fluorescing head. A, B, D, F-H: Banda Sea, C & E: Red Sea.

Figure 12: Fluorescence in fish: Detailed fluorescent pictures of *Anampses meleagrides* (A, B; both overlay of GFP and CY5 filter), *Doryrhamphus excisus* (C; overlay of mCherry and CY5 filter), *Eviota atriventris* (D, E; both overlay of GFP & CY5 filter), *Eviota nigriventris* (F-I; F: overlay of GFP, CY5, mCherry filter; G: mCherry and CY5 filter; H: brightfield & CY5 filter; I: mCherry filter), *Cirrhilabrus aquamarinus* (J; mCherry filter), Pictures were taken on a Thunder microscope (Leica, Germany).

Figure 13: Fluorescence in fish: Detailed fluorescent pictures of *Cirrhilabrus aquamarinus* (A; brightfield & Cy5 filter), Pair of *Synchiropus sycorax* (B; ♀ left and ♂ right; overlay of brightfield and Cy5 filter), first dorsal fin of *Synchiropus sycorax* ♂ (C; brightfield and Cy5 filter), detailed fluorophores of *Synchiropus sycorax* (D-F; Cy5 filter), fluorescent patch around the eye of *Synchiropus sycorax* ♂ (G; Cy5 filter). Pictures were taken on a Thunder microscope (Leica, Germany).

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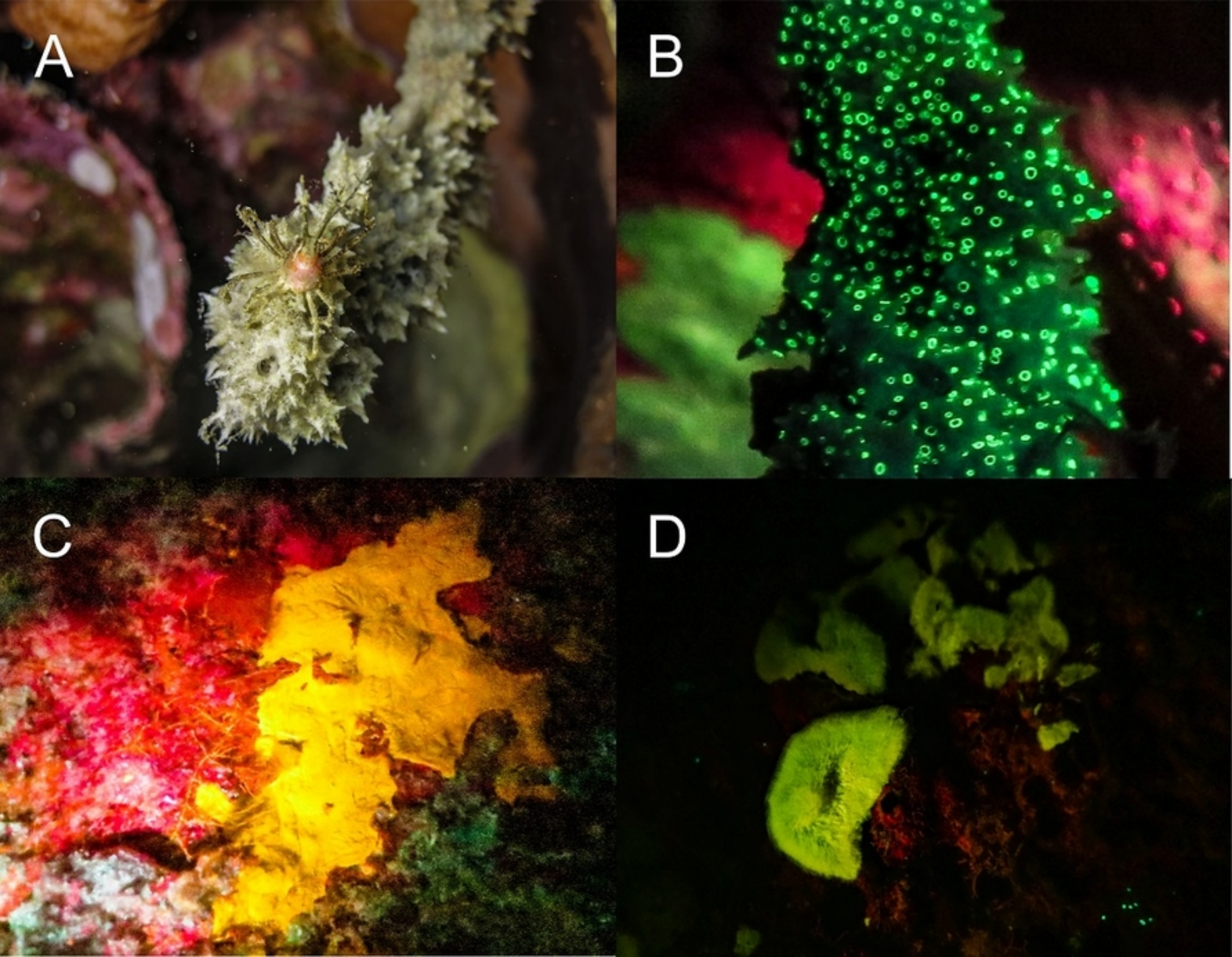
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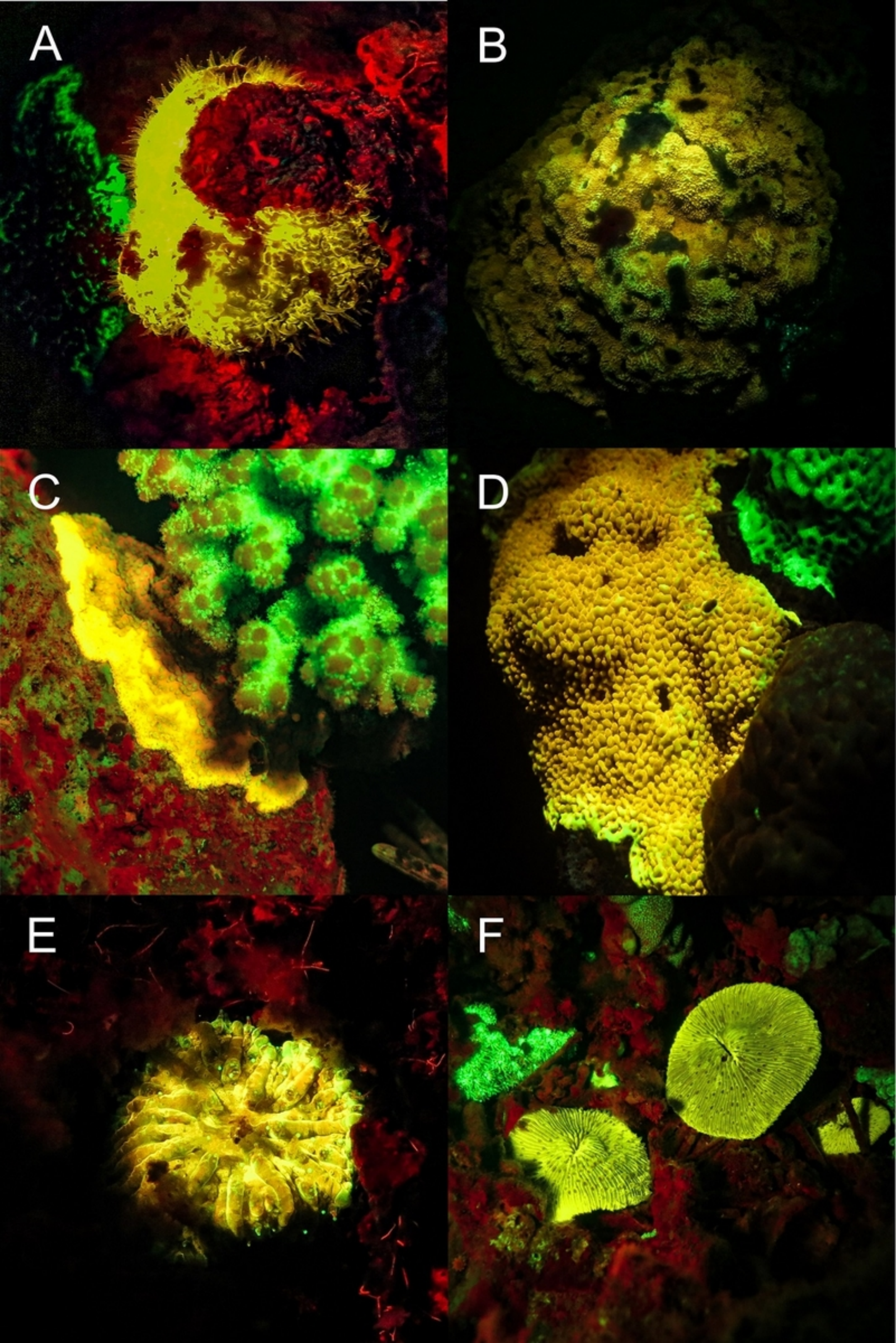
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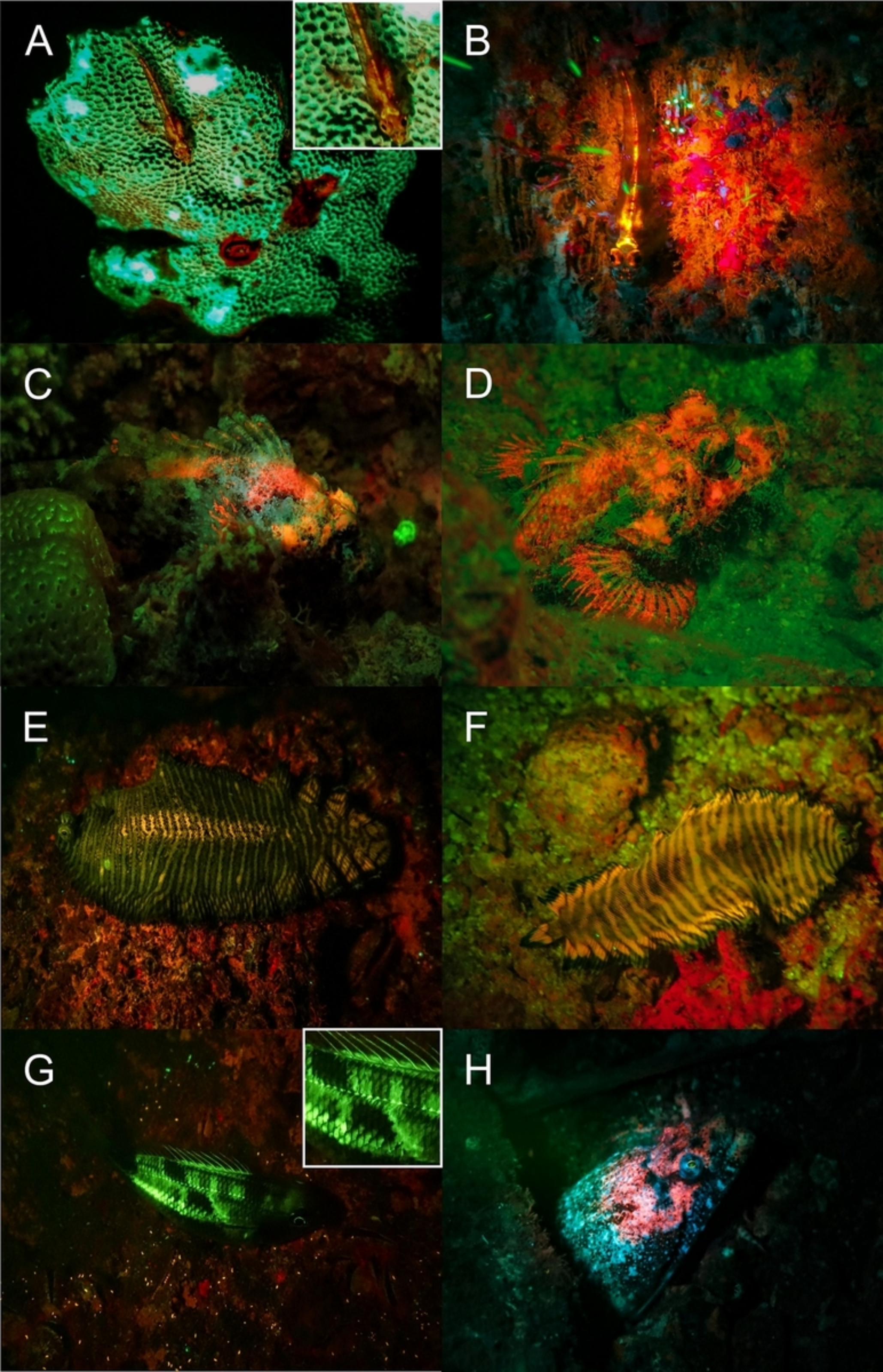
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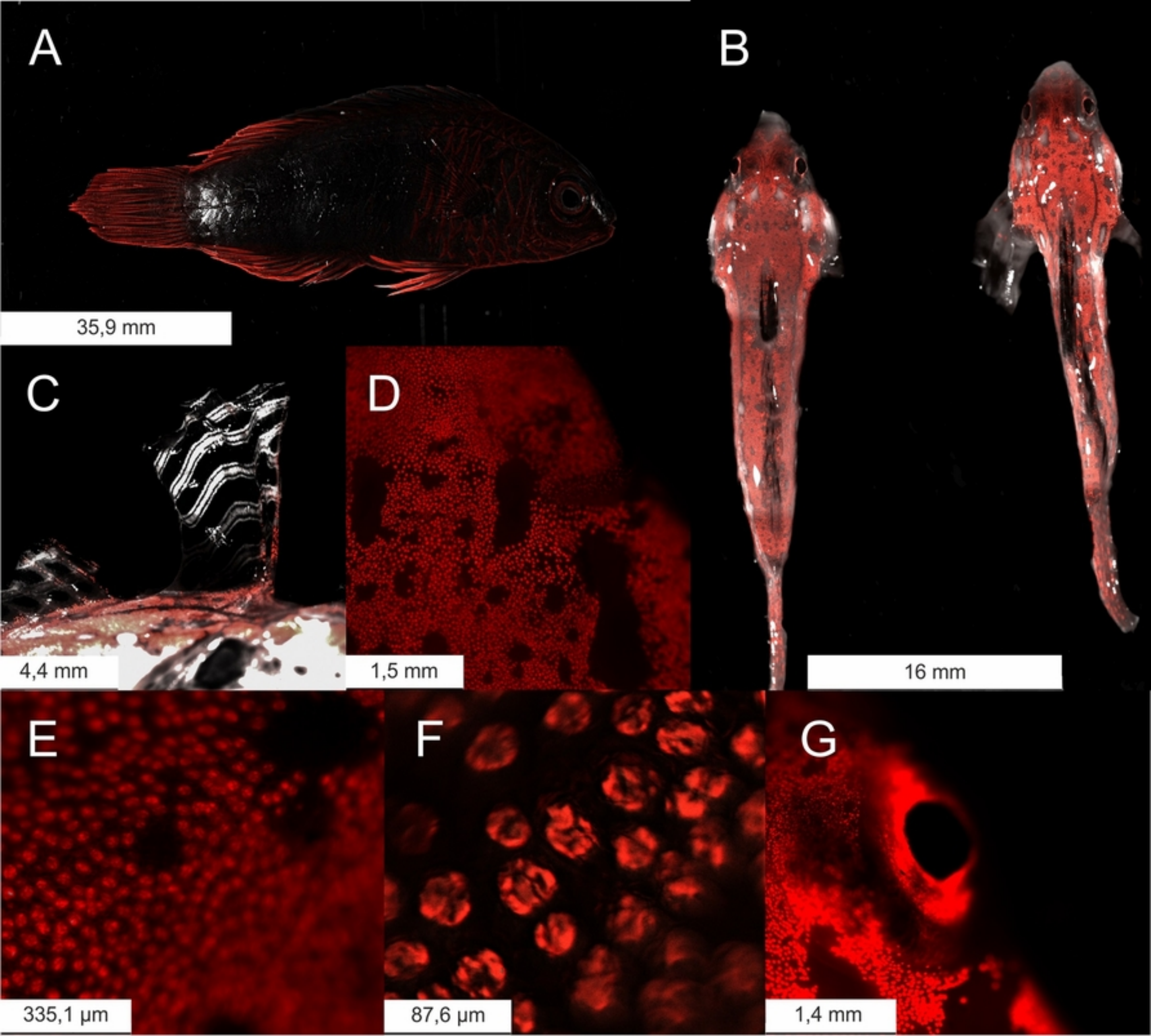
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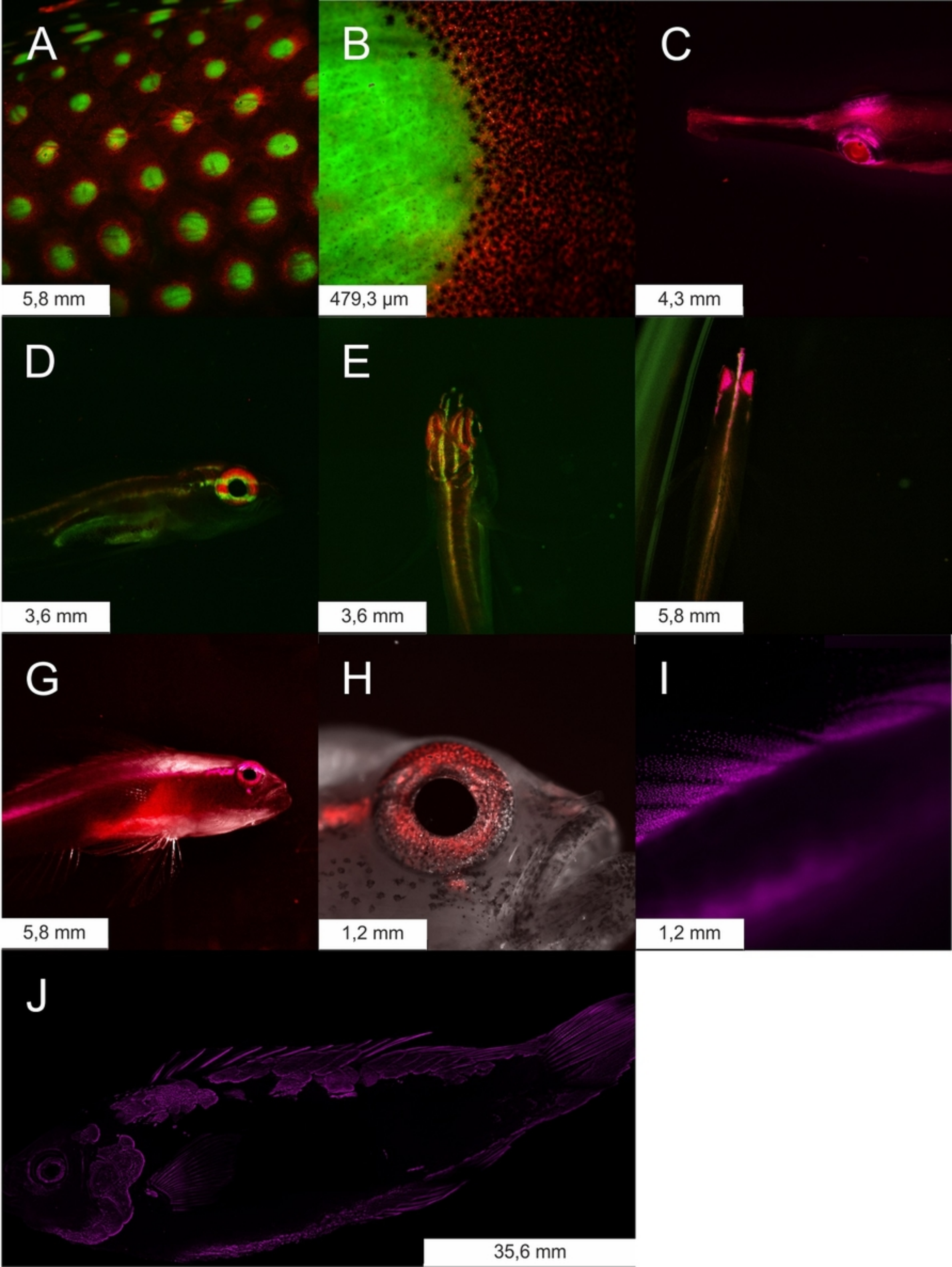
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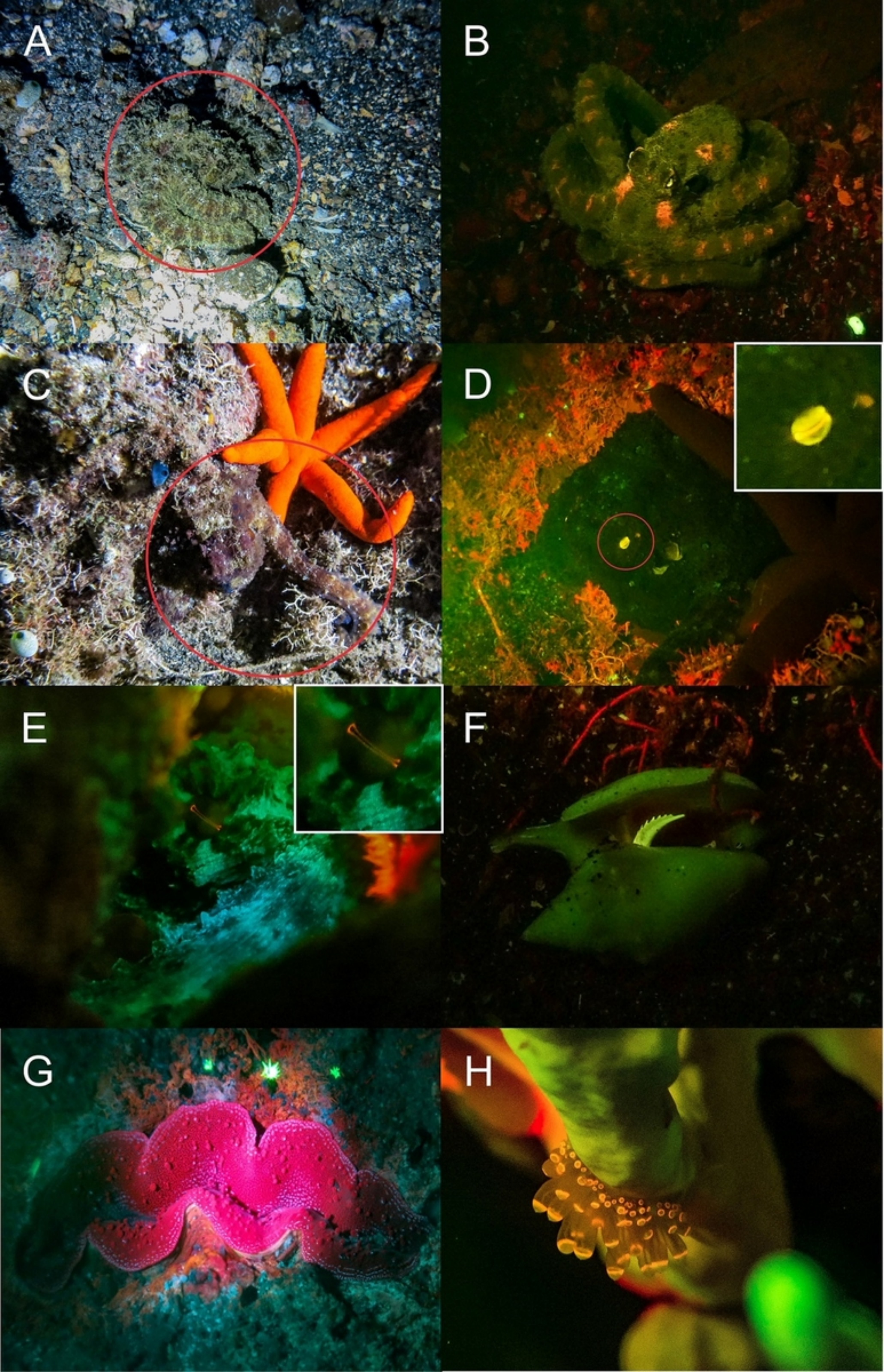
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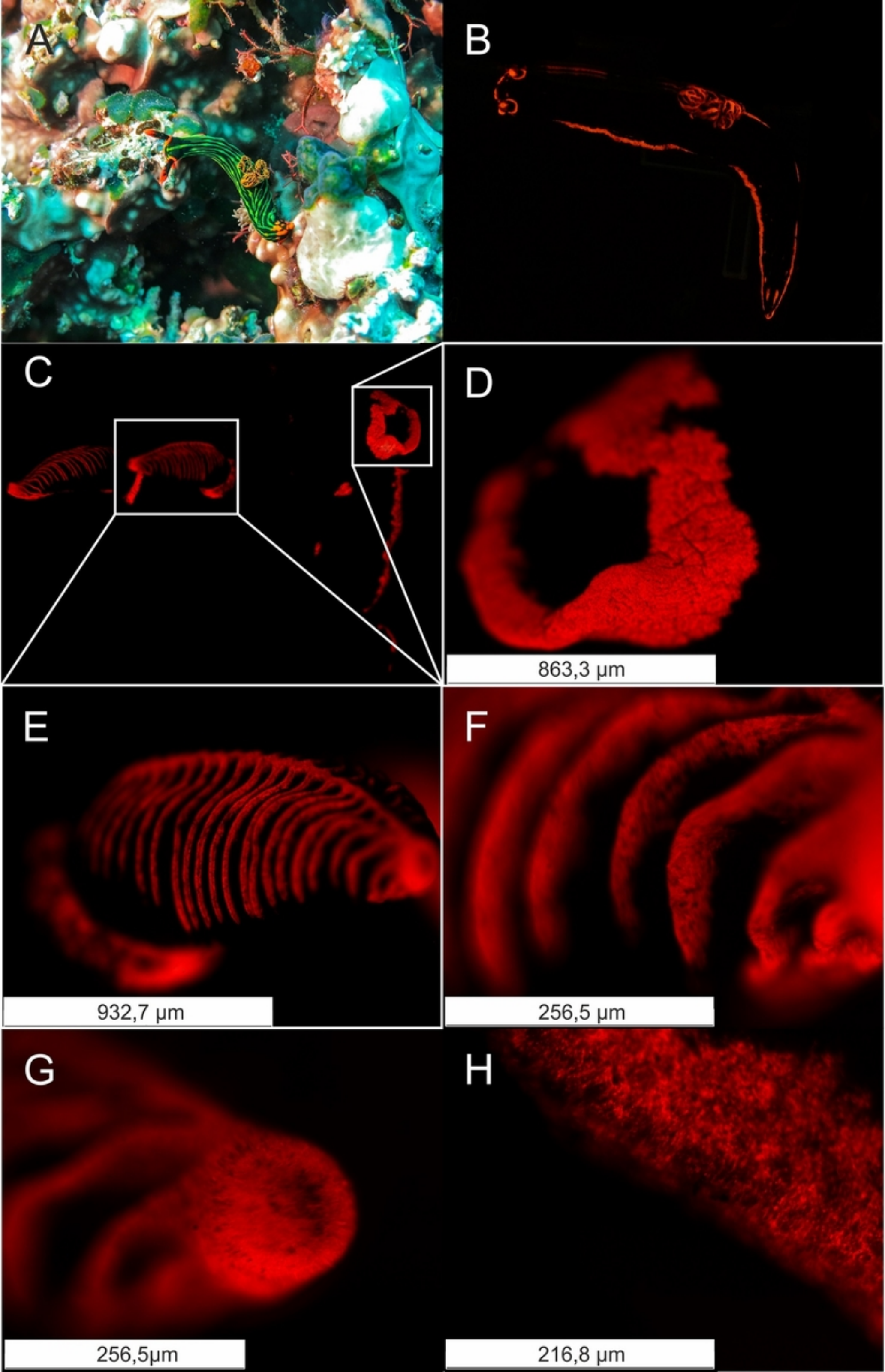
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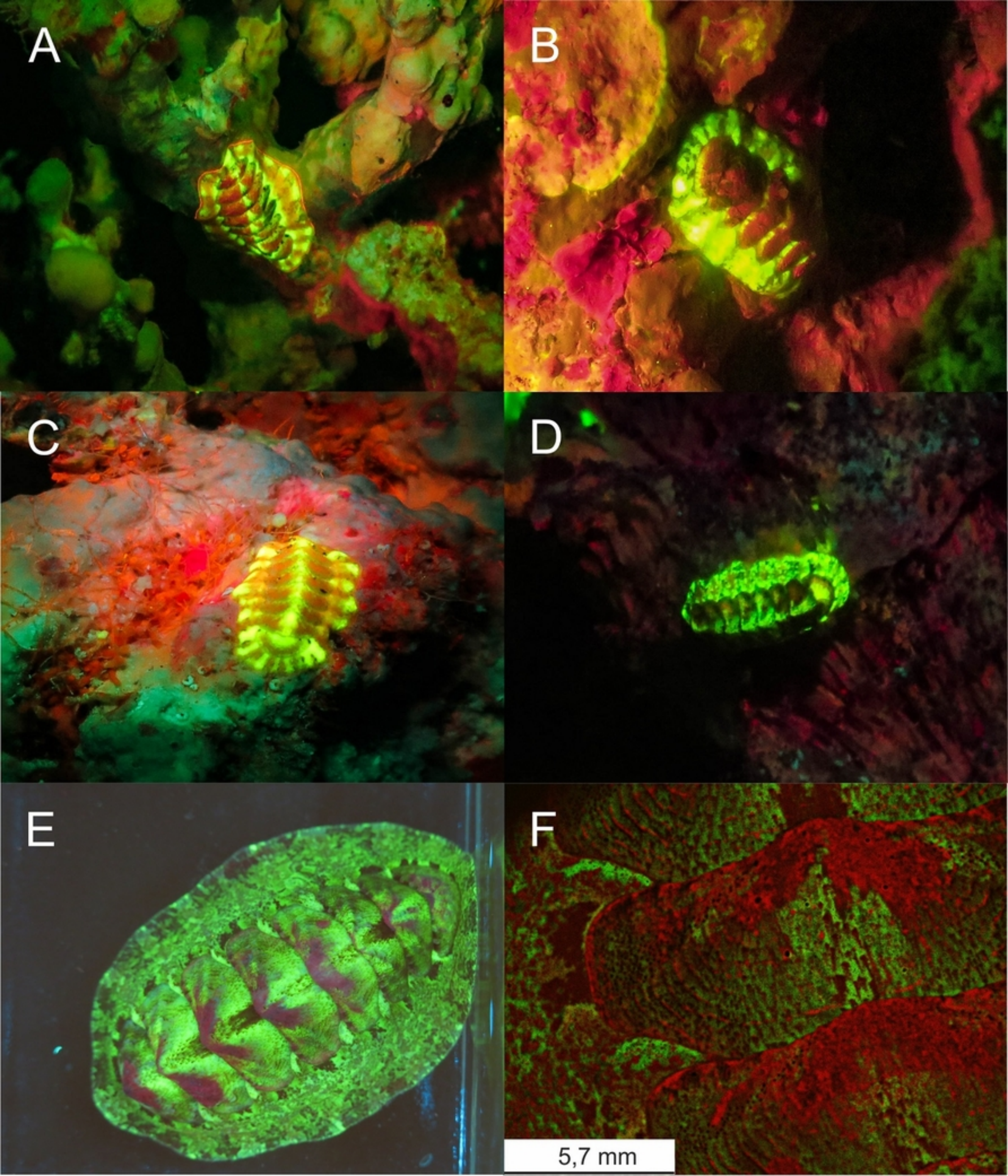
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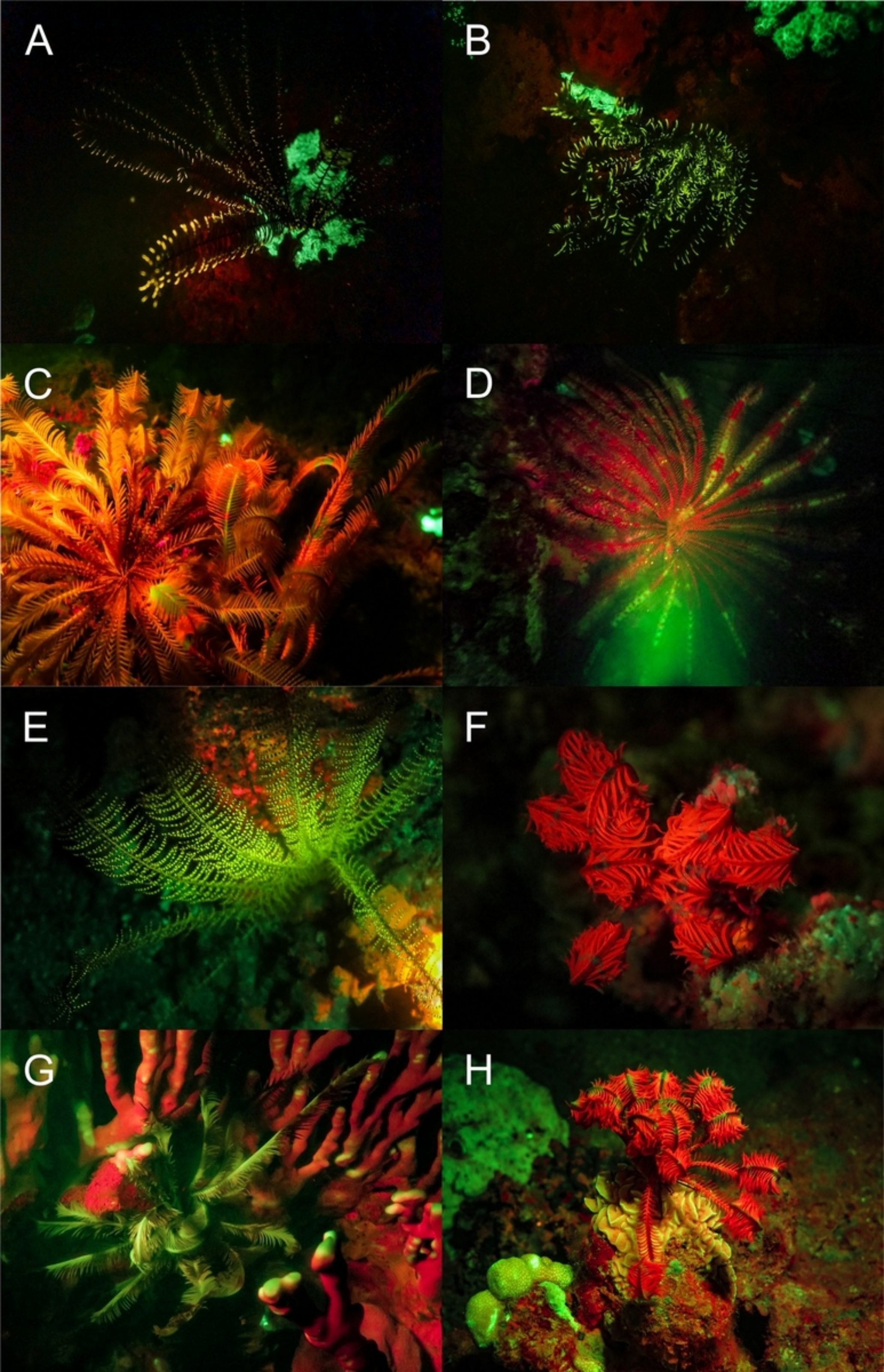
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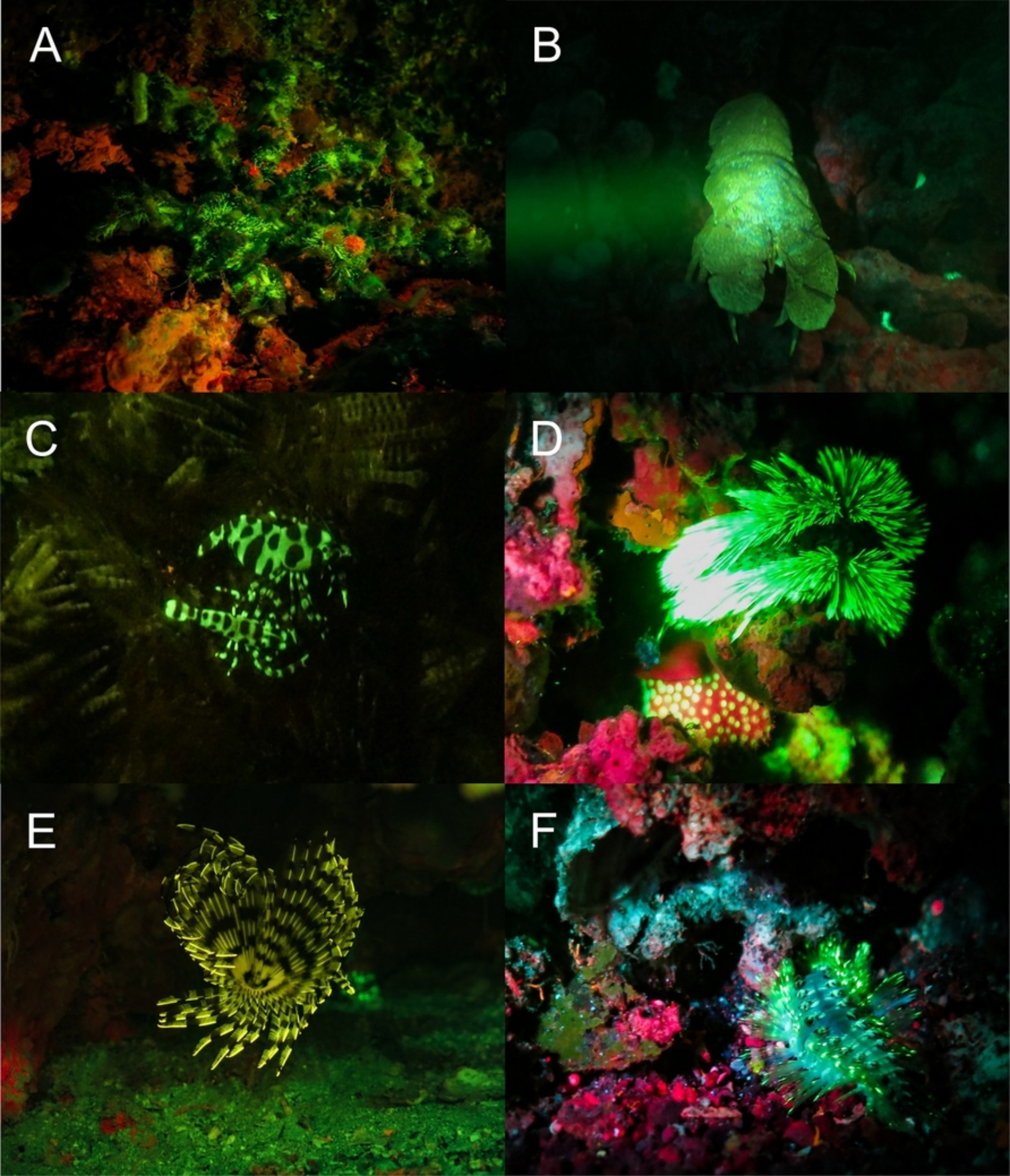
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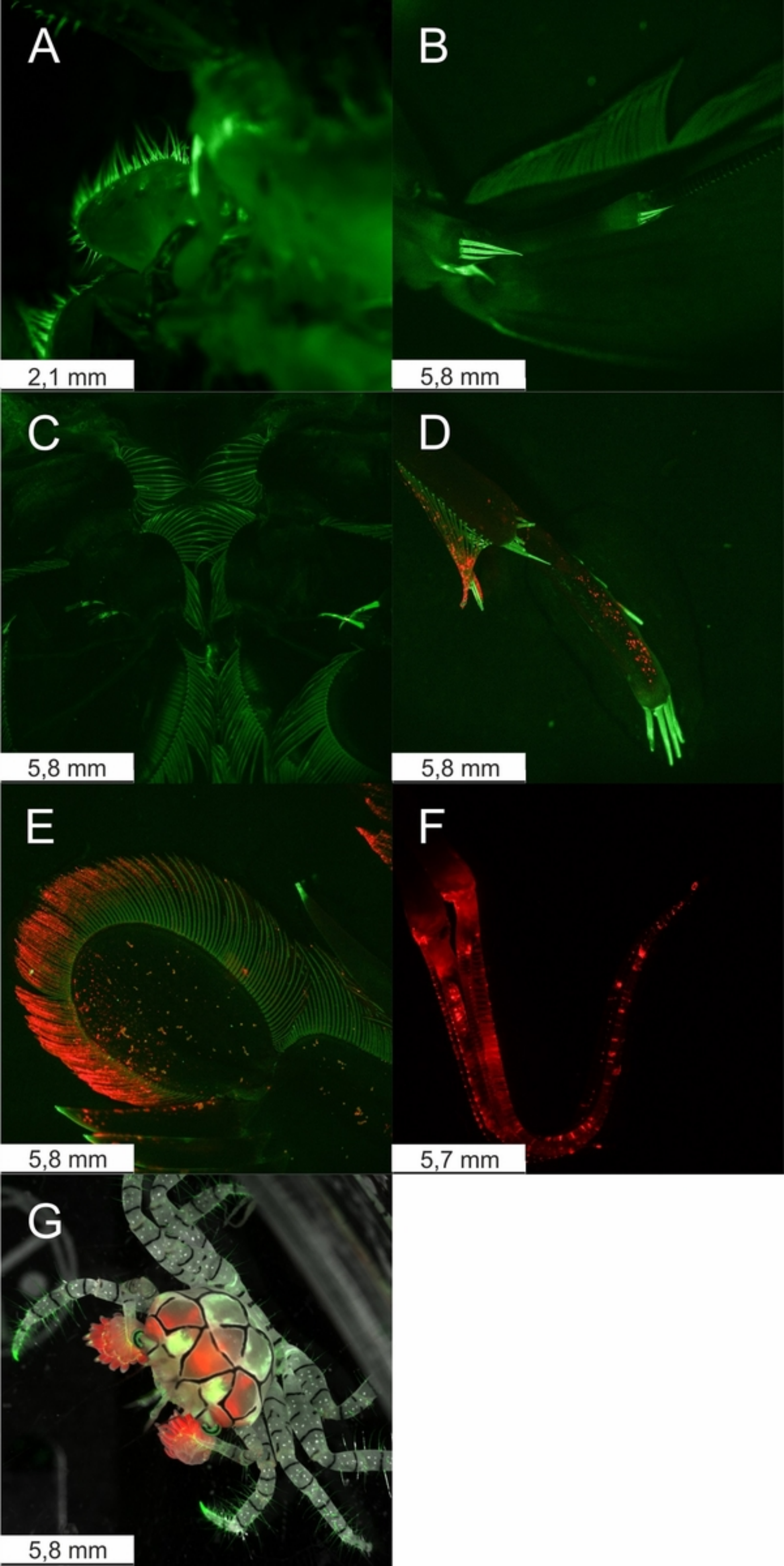
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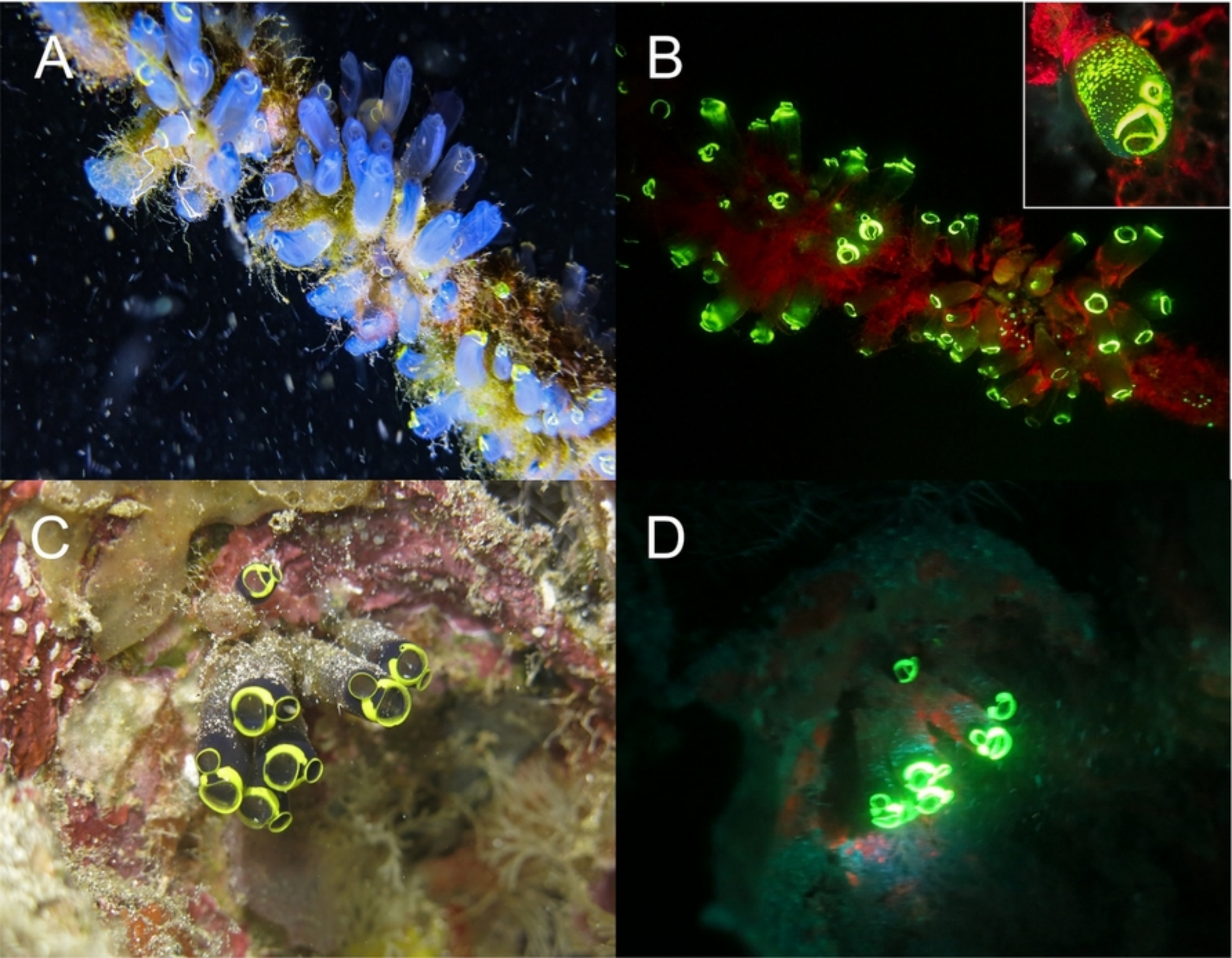
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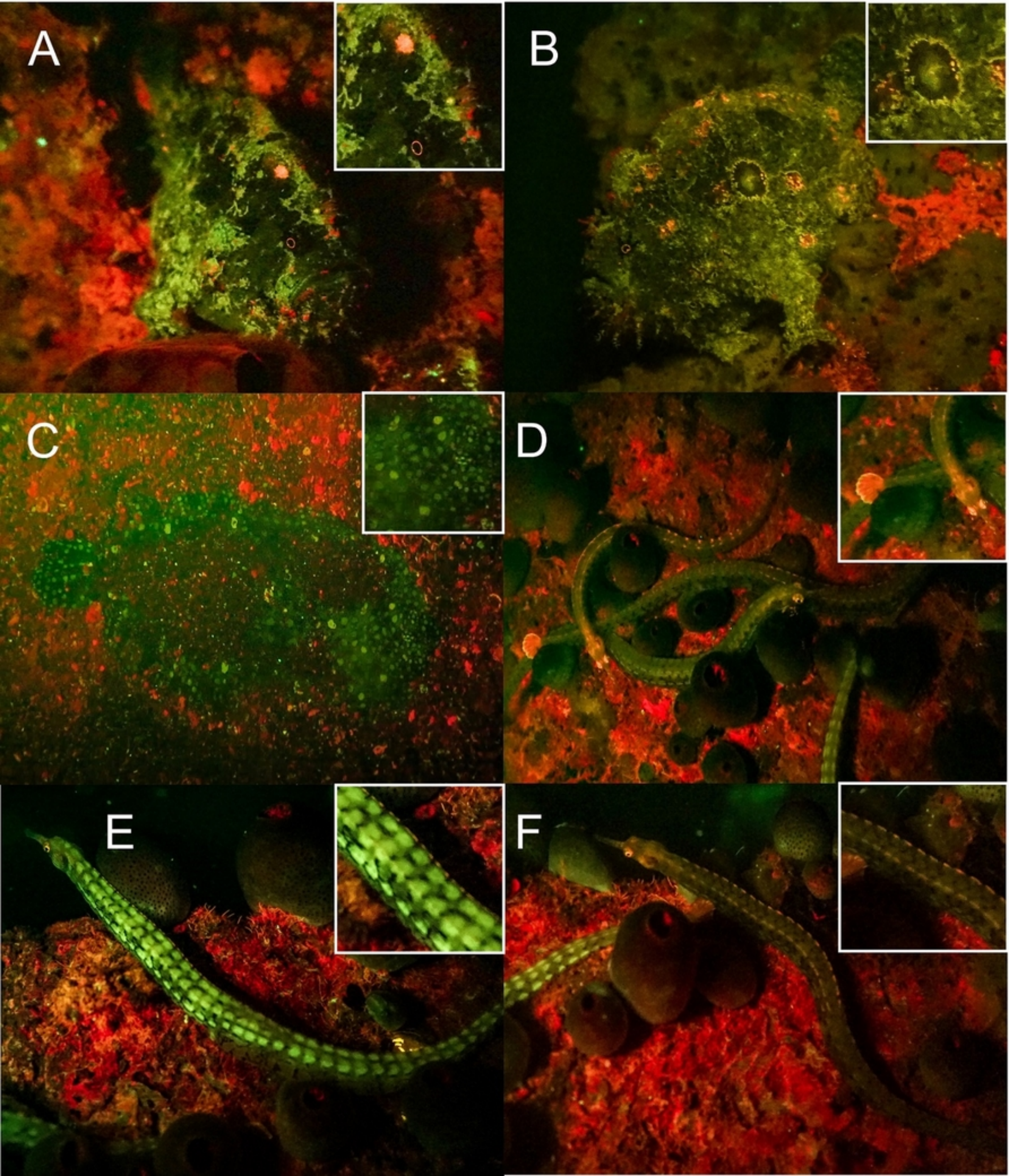
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