Marine Macroalgae: Biodiversity from Indian Waters

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Marine ecosystems are the largest aquatic ecosystems on our planet, sustaining almost 50% of the overall world's biodiversity. Marine and terrestrial environments rely on various ecosystems, such as intertidal zones, tidal zones, the deep sea, coral reefs, salt marshes, estuaries, lagoons, and mangroves, which are crucial for their sustainability. Algae are autotrophic plants that live mostly in water and come in many different types, from *Chlamydomonas*, *Chlorella* and Diatoms, which are single-celled organisms, to *Fucus*and *Sargassum*, which are multicellular organisms. The classification of marine algae encompasses two primary categories: marine microalgae and marine macroalgae. Marine microalgae, often known as phytoplankton, are exclusively observable with the use of microscopes. Marine macroalgae, also known as seaweeds, seaplants, or aquatic plants, encompass all types of marine algae that are observable without the aid of microscopes (Ranjith et al., 2018).

Forefathers of marine algae research

Carolus Linnaeus, known as the "Father of Taxonomy," coined the term "algae" in 1753, which means "sea weeds" in Latin. Felix Eugen Fritsch, known as the Father of Algology or Phycology, gave the most authentic and comprehensive algal classification. Prof. M.O.P. Iyengar (1886–1966) was an Indian botanist and psychologist who worked on algal structure, cytology, reproduction, and taxonomy. He is known as the "father of Indian phycology" or "father of algology in India

Taxonomic history of marine algae research in India

In 1672, Hermann made the initial collection of algal specimens from the Indian Ocean. He specifically gathered *Amphiroa*, a type of coralline alga, from the Cape of Good Hope in South Africa. In 1768, J.G. Koenig (1728–1789) conducted a series of comprehensive marine algal collections from the coast of Tranquebar, South India, during his voyage to India under the guidance of a Morivian missionary (Srinivasan, 1965). Foreign workers led several expeditions to collect seaweed from the Indian coasts during the 18th and 19th centuries. These expeditions included the Galathea expedition (1845-1847), Novara (1857-1859), Preussische (1859-1863), Challenger (1872-1876), Investigator (1890-1892), and Siboga (1899-1900). Nevertheless, the surge in algal research in India occurred just in the late AD's, when Prof. Iyengar (1886–1966) released a publication in 1927 detailing the seaweeds found on Krusadai Island in the Gulf of Mannar. Subsequently, he authored a collection of publications about algal studies. Boergesen (1928–1938) subsequently authored a collection spanning from 1928 to 1938, wherein he documented around 150 taxa, encompassing 5 novel genera and 38 species, originating from the western coast of India, with a special focus on the coastal regions of Bombay and Gujarat (Palanisamy et al., 2020).At the same time, numerous other researchers were actively exploring a variety of marine algae from various parts of the country.

General morphological structure of marine macroalgae/seaweeds:

Macroalgae lack true leaves, stems, and roots, but they have a few common structures with those of terrestrial plants. Their thalloid body consists of a holdfast, stipe, blade, and reproductive structures (Fischer and Hureau, 1985; Carpenter and Niem, 1998).

- Thallus: The simple vegetative plant body, no matter the growth form, is undifferentiated into true leaves, stems, and roots.
- Blades: The flattened leaf-like portions are calledblades, which are either rounded or pointed sheets or filaments. The blades are not true leaves because they lack veins.
- Frond: This term used to refer to stipe and blade together; these are either branched or tufted.
- Gas-filled bladders or floats: The gas-filled bladders or floats aid the plants in

maximizing sunlight exposure.

- Stipe: a stem-like structure not found in all seaweeds. The stipe allows a place for the attachment of the blades, which in turn provides long and tough support (e.g., Giant Kelp).
- Holdfast: A small, anchor-like, root-like structure that holds the seaweed at the bottom to any substratum.

Macroalgal growth, life history and reproduction

Seaweed typically initiates its life cycle as either a spore or a zygote, or in culture, as propagules or cuttings. After the process of settling and attachment in the substratum, germination, growth, and development occur, ultimately resulting in the formation of an adult or mature plant. This mature plant can then engage in either asexual or sexual reproduction (Lobban et al., 1985). There is a growing body of evidence suggesting that, in addition to external elements such as light and temperature, internal factors such as morphogenetic factors, such as hormones, may play a role in the processes that contribute to the formation and preservation of thallus integrity (Jacobs, 1985).

The life cycle of mature members of green, brown, and red seaweeds involves a recurring pattern of two or three somatic generations that exhibit either isomorphism (having the same morphology) or heteromorphism (having various morphologies). The sporophyte (2N) undergoes meiotic division to generate spores, which then grow into gametophytes (N) to facilitate mitotic gamete production. The process of gamete fusion results in the formation of a zygote, which subsequently develops into a sporophyte, completing the cycle. In certain species of red algae, such as Gracilaria, the carposporophyte (2N) is generated within the female gametophyte (N) following the fertilization of an egg by spermatia derived from the male gametophyte. In carposporangia, the carposporophyte generates carpospores (2N) that are then liberated and undergo germination into tetrasporophyte (2N), which in turn produces tetraspores (N) by the process of meiosis. The tetraspores subsequently differentiate into either female or male gametophytes (N), thus concluding the plant's life cycle (Carol, 2006).

Seaweeds have the ability to reproduce or spread in both temporal and spatial dimensions through asexual and sexual mechanisms. The asexual technique can be achieved by two methods: 1) vegetative regeneration from naturally or intentionally created fragments; or 2) the creation of non-motile or motile spores in structures known as sporangia. The former is referred to as an aplanospore, which is generated within the aplano sporangium, while the latter is known as a zoospore, which is formed within the zoosporangia. Sexual reproduction involves the fusion of gametes derived from either simple or differentiated gametangia. In the case of differentiated gametangia, an antheridium produces male gametes, while an oogonium produces female gametes. Fertile regions can be observed on the surfaces of the thalli in the more sophisticated stages of the red and brown algae. Male gametes, known as spermatia, can be grouped together in cavities called conceptacles. On the other hand, female reproductive organs, such as tetrasporangia, can form separate aggregations called sorus (FAO, 1988).

According to Trono and Fortes (1988), certain specialized branches of spore production are referred to as "receptacles," yet in other cases, certain portions of these branches undergo conversion into fertile structures known as stichidium. Female gametophytes of red seaweeds, such as *Gracilaria*and *Eucheuma*, develop stunted or sessile cystocarps on their surfaces. These cystocarps contain the carposporophyte and are covered by a pericarp.

Seven-kingdom classification of living organisms including macroalgae

Ruggiero et al. (2015) propose a two-superkingdom (prokaryotic and eukaryotic) and seven-kingdom classification with the extension of Cavalier-Smith's six-kingdom schema (Cavalier-Smith, 1998). *Cellular level:* Prokaryota (unicellular): bacteria, e.g., *Staphylococcus,* and Archaea, e.g., *Halobacterium* (Carl et al., 1990). Eukaryota (mainly multicellular, with a few exceptions): Protozoa, e.g., Amoebozoa; Chromista, e.g., diatoms; brown algae; Plantae, e.g., land plants; red or green algae; fungi, e.g., fungus; and Animalia, e.g., fishes, mammals. *Non-cellular level:* Stefan Luketa (2012) created two additional domains (no RNA/DNA-infectious), i.e., prions and viruses.

Taxonomic identification of marine macroalgae

Marine macroalgal taxonomy is a complex field, partly because it is evolving, whereby species and genera are frequently changed, e.g., *Porphyra*to *Pyropia*, *Enteromorpha* to *Ulva*, and *Laminaria* to *Saccharina*. Understanding the cytological properties of seaweeds is crucial for comprehending their fundamental adaptations at this lower level of organization, in addition to their utility as tools in marine macroalgae taxonomy. However, that classification is based on the combination of several characters (**Table 1)**.The categorization of algae at the division level primarily relies on many key criteria, including

- the presence of photosynthetic pigments;
- the availability of food reserves.
- the composition of cell walls; and
- other significant characteristics of the ultrastructure.

Collection and preservation of marine macroalgae

Collection of macroalgae

- Intertidal collection (low tide; 1-2 hours before low tide; description of the site location, topography, etc.).
- Material required: polyethylene bags, knives or scalpels, labeling materials, rubber bands, field notes, long rope (about 50 m long), monopane balance, etc.

Survey methods

- Line/belt transect or quadrat or random sampling or video transect

Sample preservation (Wet/Dry)

- Wet preservation adhering materials (5–10% formaldehyde in seawater should be prepared to preserve the seaweed sample).

Sectioning and staining of marine macroalgal samples

- Sectioning: healthy specimen; rinse specimen - use a sharp scalpel or microtome to cut thin cross-sections of the seaweeds (thin sections - 10μM)
- Staining: A drop of the dye was placed via a glass rod on the section (wait for two minutes for penetration). The dye used are
- Azure II: Red algae: red tones; brown algae: blue tones; and green algae: purple color
- Methylene blue: Blue colour *Acanthophora* spp. forms a purple color.
- Thioflavin: Thioflavin: yellow, sometimes brown; Brown colour - cuticle and epidermal cells.

Table 1. General classification and features of the seaweed major divisions (adapted from FAO, 1988).

SN	Division	Pigments	Plastids	Cell wall	Stored food	General morphology	Reproduction
1	Ulvophyceae/Chlorophyceae	Chl a Chl b	Present	Outer layer - Pectic & Inner layer - Cellulose	Starch	Microscopic - filamentous to coenocytic; to various macroscopic forms	Asexual. Sexual
2	Phaeophyceae	Chl a Chl c Fucoxanthin	Present	Cellulose and alginic acid	Laminarin & mannitol	Freely branched; filaments to macroscopic	Asexual. Sexual
3	Florideophyceae/Rhodophyceae	Chl a Chl d	Present	Cellulose & gelatinous or sulfatedgalactans such as agar, carrageenan, furcellaran	Floridean starch	Microscopic-filamentous;macroscopic forms	Asexual. Sexual

Keys to major classes - Characters

- 1a Thallus green to yellowish green; chlorophyll b present; zoospores flagellate generally green; cell wall outer layer pectic and an inner layer cellulose; sometimes calcified; photosynthetic product is starch

. . . . . Ulvophyceae/Chlorophyceae (Green algae)

- 1b. Thallus brown or red; chlorophyll b absent; zoospores flagellate or eflagellate…..2
- 2a. Thallus brown to pale brown to reddish brown in color; xanthophyll pigments; chlorophyll a and c present; reserve food mannitol and laminarin zoospores always flagellate

. . . . . Phaeophyceae (Brown algae)

- 2b. Thallus red to yellowish red to dark greenish red in color r-phycoerythrin; chlorophyll a & d present; reserve food floridean starch; zoospores always a flagellate

. . . . . Florideophyceae/Rhodophyceae (Red Algae)

Green algae

Major pigment is chlorophyll; very common in salinities varying (bays and estuaries, tide pools); simple thallus when compared to other algae. Many forms are filamentous to thin sheets.

Green algaekeys to major orders in India (adapted from Oza& Zaidi, 2001).

- 1a. Thallus filamentous, simple or branched; cells usually cylindrical to barrel shaped, multinucleate …..2
- 1b. Thallus not filamentous; cells variable in shape, uni- or multinucleate …..3
- 2a. Thallus intertwined, forming a mat-like structure …..Acrosiphoniales (*Acrosiphonia orientalis*)
- 2b. Thallus freely branched, not forming a mat-like structure …..Cladophorales (*Cladophora glomerata*)
- 3a. Thallus is usually foliose, flat, ribbon-shaped, or tubular …..4
- 3b. Thallus, usually siphonous, spongy, or feather-like; rarely foliose; multinucleate …..5
- 4a. Thallus foliose, small, up to 30 cm long …..Ulotrichales *(Monostroma latissimum)*
- 4a. Thallus foliose, tubular or ribbon shaped, up to 2 m long …..Ulvales (*Ulva reticulata*)
- 5a. Thallus spongy, cup-like, or matted with clavate to cylindrical vesicles; holdfast rhizoidal or tenaculum type …..Siphonocladales (*Valoniopsis pachynema*)
- 5b. Thallus feathery to grape like or foliaceous …..Bryopsidales (*Caulerpa racemosa*)

Brown algae

The major pigment is fucoxanthin; color varies from olive green to dark brown; and yellow-brown pigments mask the color of chlorophyll.

Brown algae keys to major orders in India (adapted from Oza & Zaidi, 2001).

- 1a. The life cycle lacks alternation of generations; the sporophytic phase is absent, represented by only the gametophyte phase…..Fucales *(Sargassum wightii)*
- 1b. The life cycle exhibits an alternation of generations, represented by both sporophytic and gametophytic phases….. 2
- 2b. Thallus shows apical growth….. 3
- 2b. Thallus shows trichothallic growth…..4
- 3a. Thallus polysiphonous, grows with a single prominent cell …..Sphacelariales *(Sphacelaria rigidula*)
- 3b. Thallus, not polysiphonous, grows with one to many apical cells, fronds flat, blade-like, non-heterotrichous…..Dictyotales *(Dictyopteris australis)*
- 4a. Thallus heterotrichous, filamentous, rarely pseudoparenchymatous…..Ectocarpales *(Ectocarpussiliculosus)*
- 4b. Thallus non heterotrichous, hollow or sac-like…..Scytosiphonales *(Colpomenia sinuosa)*

Red algae

Major pigments are phycobilins, mostly red rather than green or brown; some have calcium carbonate within their cell walls. Coralline red algae shows smooth or rough encrusting growth on rocks.

Red algae keys to major orders in India (adapted from Oza& Zaidi, 2001)

- 1a. Thallus foliose, filamentous or membranous; cells with stellate chromatophores; protoplasmic connection absent…..Bangiales *(Porphyra kanyakumariensis)*
- 1b. Thallus filamentous-complex, often massive forms, protoplasmic connection present….. 2
- 2a. Auxiliary cells absent….. 3
- 2b. Auxiliary cells present….. 5
- 3a. Gonimoblast filaments intermingled with nutritive filaments…..Gelidiales *(Gelidium micropterum)*
- 3b. Gonimoblast filaments, usually not intermingled with nutritive filaments, develop directly from the fertilized carpogonium or rarely from the hypogynous cell….. 4
- 4a. Central axial cell not visible in the pseudoparenchymatous thallus, carpogonium branches 2-celled…..Gracilariales *(Gracilaria edulis)*
- 4b. Central axial cell visible in the pseudoparenchymatous thallus, carpogonium branches 3-celled …..Bonnemaisoniales
- 5a. Auxiliary cells form only after fertilization…..Ceramiales *(Centroceras clavulatum)*
- 5b. Auxiliary cell formed before fertilization….. 6
- 6b. Thallus is usually calcified; tetrasporangia develops in conceptacles…..Corallinales *(Amphiroa fragilissima)*
- 6b. Thallus is usually not calcified; tetrasporangia does not develop in conceptacles….. 7
- 7a. Auxiliary cells formed in special accessory branches…..Cryptonemiales *(Grateloupia filicina)*
- 7b. Auxiliary cells are not formed in special accessory branches or branch clusters….. 8
- 8a. Cells formed from the supporting cell of a carpogonial branch act as the auxiliary cell …..Rhodymeniales *(Champia parvula)*
- 8b. Intercalary cells of a vegetative filament act as the auxiliary cell…..9
- 9b. Pit plugs are always membranous, spermatangialsori are large, and gonimoblast filaments develop in upward or downward directions…..Gigartinales *(Catenella impudica)*
- 9b. Pit plugs are always naked, spermatangialsori are small, and gonimoblast filaments develop in an upward direction only …..Ahnfeltia Les *(Ahnfeltia plicata)*

Classification of living algae and global diversity of macroalgae

The estimated global algal diversity represents 72500 taxa, of which 50,589 species (10,556 fossil) have already been described. Algal species are represented mainly by four kingdoms (Eubacteria, Chromista, Plantae, and Protozoa), representing sixty-three classes and still growing (Guiry et al., 2024; Guiry&Guiry, 2024). There are fourteen algal phyla, of which seaweeds fall under three major phyla. Chlorophyta (chlorophyta/green algae), Heterokontophyta/Ochrophyta (includes brown algae), and Rhodophyta (Rhodophyta/red algae) come under two major kingdoms, i.e., Chromista and Plantae. Kingdom-wise living algal species and a decadal description of new macroalgal species are given in Tables 2 & 3.

Table 2: Kingdom-wise living algal species (adapted from Guiry et al., 2024)

Kingdom	Genera	Species	Species (%)	Fossil	Living	Extant(%)
Chromista	2932	29,200	47.76	4709	24,778	48.75
Plantae	2858	21,170	34.62	2257	19,105	36.88
Total	**7707**	**61,145**		**10,556**	**50,589**	

Table 3: Decadal description of new species(adapted from Guiry et al., 2024)

Phylum/class	2012-2022	Average
Chlorophyta	507	51
Phaeophyceae	160	16
Rhodophyta	770	77

Diversity of macroalgae

There are about 12,000 species represented by Chlorophyta (Ulvophyceae; 22.97% with 2,695 species in 527 genera), Heterokontophyta (Phaeophyceae; 9.11% with 2124 species in 346 genera), and Rhodophyta (Forideophyceae; 94.72% with 7,155 species in 990 genera). The estimated total number of species is between 8000 and 10500; more than 841 species are represented in the Indian waters (Radulovich et al., 2015; Ganesan et al., 2019), exhibiting regional species richness and global diversity patterns. Worldwide, 291 seaweed species are commercially used; due to their cultivation success and biomass value, seaweed is now being farmed in more than 50 countries (FAO, 2016). Taxonomy, species diversity, and distribution of seaweed have been well studied in the Indian seas (Krishnamurthy and Joshi, 1970; Untawale et al., 1983; Oza and Zaidi, 2001; Sahoo et al., 2001; Rao and Gupta, 2015; Kaliaperumal., 2017). The studies show that the seaweeds were abundant in Gujarat, Tamil Nadu, the Andaman and Nicobar Islands, and the Lakshadweep Islands. Recently, from the Indian waters, 844 species were represented, of which 434 were Rhodophyta, 191 were Ochrophyta, and 216 were Chlorophyta (Mantri et al., 2020). The comparison of earlier reports on Indian macroalgae diversity is given in Table 4.

Table 4: Comparison of earlier report on Indian macroalgae diversity

Checklist	Title	Chlorophyta	Ochrophyta	Rhodophyta	Total
Krishnamurthy & Joshi, 1970	Genera	36	33	98	167
	Species	130	136	256	522
Untawale et al.,	Genera	44	39	120	203

1989	Species	156	141	307	604
Oza and Zaidi., 2001	Genera	43	37	136	216
	Species	216	191	434	841
Sahoo et al.,2003	Genera	45	38	138	221
	Species	184	166	420	770
Rao and Gupta, 2015	Genera	46	50	138	234
	Species	212	211	442	865
Present study	Genera	50	48	157	255
	Species	240	219	475	934

Present Indian macroalgae diversity

The distributional records of valid Indian seaweed species and country-wise seaweed diversity up to March 30, 2022, were extracted from the global AlgaeBase database (https://www.algaebase.org/). The results revealed 934 species of seaweeds, including 240 Chlorophyta (30 families and 50 genera), 219 Ochrophyta (15 families and 50 genera), and 475 Rhodophyta (49 families and 157 genera), were extracted from the database (Table 5). The Rhodomelaceae (Rhodophyta) are the most species-rich family, representing nearly 84 taxa, whereas the brown seaweed, *Sargassum* (more than 100 taxa), is the most diversified genera.

Table 5: Indian macroalgae diversity from AlgalBase Database

Class	**Order**	**Family**	**Genera**	**Species**
Rhodophyta	22	49	157	475
Ochrophyta	8	15	48	219
Chlorophyta	8	30	50	240
Total	**38**	**94**	**255**	**934**

Factors influencing marine macroalgal diversity

Environmental Conditions:

- Temperature: Different species thrive in various temperature ranges, influencing their distribution.
- Light Availability: Light intensity and quality affect photosynthesis and growth.
- Salinity: Species exhibit preferences for
- specific salinity levels.

Substrate Availability:

- Substrate Type: Macroalgae exhibit preferences for different substrate types, including rocks, sand, and other macroalgae.
- Substrate Stability: The stability of the substrate influences attachment and

growth.

Nutrient Levels:

- Nitrogen and Phosphorus: Nutrient availability influences macroalgal productivity.
- Eutrophication: Elevated nutrient levels may lead to increased macroalgal growth.

Wave Action and Currents:

- Wave Exposure: Some species are adapted to withstand strong wave action, while others prefer sheltered areas.
- Current: Macroalgae may adapt their forms based on water movement.

Importance of Marine Macroalgae

Seaweeds grow in the intertidal and subtidal regions of the sea and other aquatic bodies. Like land plants, seaweeds form the basis of the marine ecosystem's food chain; the photosynthetic pigments can produce food and form an important primary producer in the marine environment. Seaweeds have been used for food and medicine for over 14,000 years, and many tons of these plants are gathered and eaten (Reed, 1907; Dillehay et al., 2008). Seaweed has become a commercially crucial coastal product as it produces primary metabolites (structural molecules such as proteins, lipids, and carbohydrates) and secondary metabolites as bioactive compounds. They have a more comprehensive application, i.e., human nourishment, livestock feed, agricultural fertiliser, cosmetics, pharmaceuticals, and biotechnological (Leandro et al., 2019). Several seaweeds are considered structuring species in changing the coastal environment by modifying light, sedimentation rates, and hydrodynamics (Sara García-Poza et al., 2020).

Marine Macroalgae- Services and benefits to humans

Seaweeds generate socio-economic benefits and support coastal communities, thereby contributing to environmental benefits, human health, and ecosystem services.

- Environmental benefits and ecosystem services: habitat for marine organisms, bioremediators, mitigation of ocean acidification and climate change, etc.
- Human basic utilities: healthy, low-calorie food, animal feed and supplements, biofuel, biofertilizer, growth stimulants, etc.
- Industrial uses: bioactive compounds, nutraceuticals, cosmetics, industrial chemicals, etc.
- Socio-economic benefits: livelihood of coastal communities and income generation

Marine Macroalgae Biodiversity Research Gaps and Challenges

- Fixing geographical gaps to entirely record biomass and species diversity
- Strengthening the scientific community's access to data
- Expertise is needed for building capacity and national expertise for constructing an
- integrated taxonomy
- Possibilities to promote seaweed utilisation, cultivation, and sustainable harvesting in India
- Adequate technical and scientific support is required for the national seaweed policy and guidelines.

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