1. *General characteristics of algae*

Algae are a polyphyletic and highly diverse group of primarily aquatic, photosynthetic organisms studied in Phycology. They are distinct from land plants due to their lack of complex tissue organization.

- Photosynthesis and Autotrophy: Algae are photoautotrophs, synthesizing food using sunlight. They contain chlorophyll a as the central pigment, supplemented by various accessory pigments (e.g., carotenoids, phycobilins) that determine their color. They are critical primary producers, generating a substantial portion of the world's oxygen.
- Thallophytes (Avascular): Their body, the thallus, is simple and undifferentiated. Algae lack true vascular tissues, roots, stems, and leaves.
- Habitat: They are predominantly aquatic, inhabiting marine, freshwater, and brackish environments. Terrestrial forms exist (on moist soil or bark) but are dependent on environmental moisture.

Cellular Organization: Most algae are eukaryotic (possessing a nucleus and organelles). The major exception is the Cyanobacteria (blue-green algae), which are prokaryotic.

- Reproduction: Algae employ a broad spectrum of reproductive strategies, including vegetative (fission, fragmentation), asexual (spore formation), and complex sexual processes (gamete fusion).
- Embryo and Gametangia: They are characterized by the absence of a protected embryonic stage. Their sex organs (gametangia) are typically unicellular, or, if multicellular, all cells are fertile.

2. Structure and Morphology of Algae

The thallus morphology of algae exhibits an extraordinary range, from microscopic single cells to macroscopic giants.

A. Diversity in Thallus Morphology

Morphological Type	Description	Representative Example
Unicellular	The entire organism is a single cell, which may be motile (flagellated) or non-motile.	Chlamydomonas, Diatoms
Colonial	An aggregate of cells embedded in a matrix, functioning as a unit with little specialization.	Volvox
Filamentous	Cells arranged in chains; structures can be unbranched or branched.	Spirogyra, Cladophora
Siphonaceous (Coenocytic)	A large, multinucleate, tubular body without the formation of internal cross-walls (aseptate).	Vaucheria
Parenchymatous	Cells divide in three dimensions, resulting in a complex, tissue-like structure that may possess holdfasts, stipes, and blades.	Kelp (Laminaria), Sea lettuce (Ulva)

B. Eukaryotic Algal Cell Characteristics

The eukaryotic algal cell includes several specific structural components:

Cell Wall: The wall composition varies chemically between groups, featuring materials such as cellulose (Green Algae), alginic acid (Brown Algae), or silica (Diatoms).

- Chloroplasts: These organelles contain pigments and often enclose a pyrenoid, a protein center for the storage of reserve carbohydrates (like starch).
- Flagella: Present on motile cells (gametes or spores). They adhere to the universal eukaryotic 9+2 microtubule arrangement and are key taxonomic markers based on their number and insertion.

Thallus Organisation in Algae

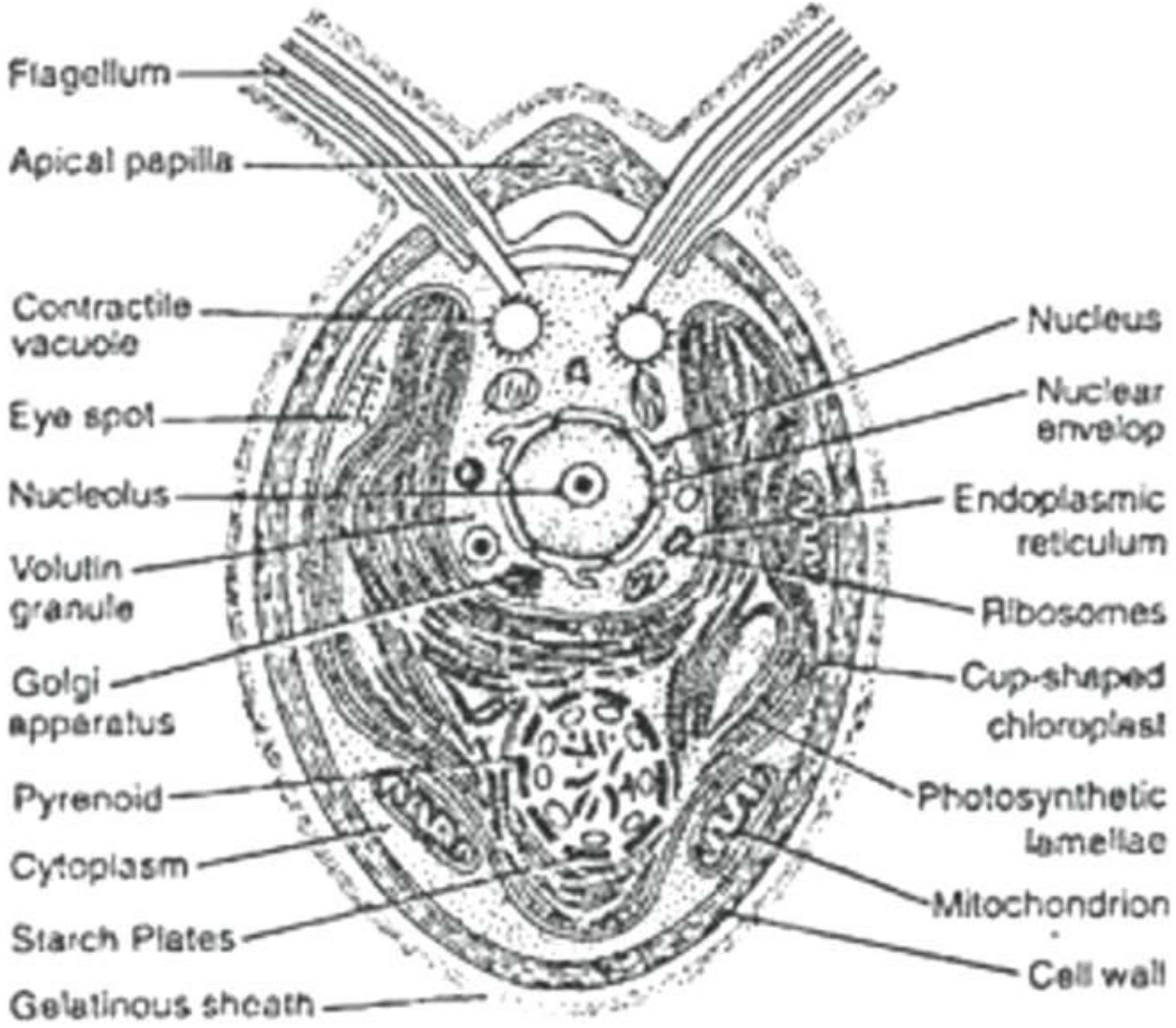


Fig. : Structure of an eukaryotic cell (*Chlamydomonas*) under electron microscope

2. Structure and morphology of algae

The body of the alga, known as the thallus, is its fundamental structure, exhibiting extreme morphological variation from microscopic phytoplankton to massive seaweeds. This diversity reflects successful adaptation to aquatic life, optimizing the capture of sunlight and the direct absorption of nutrients.

2.1.Morphological classifications

Algae are grouped primarily by size, which determines their ecological function:

- Microalgae (e.g., *Chlamydomonas*, Diatoms):

  Structure: Primarily unicellular or small, loose colonies with a high surface area-to-volume ratio.

  Function: They form the majority of phytoplankton, the base of aquatic food webs. Many are motile, using flagella to regulate their position in the water column.

- Macroalgae (Seaweeds / Goémons):

  Structure: Large, multicellular organisms that are benthic (attached to the bottom).

  Function: They create critical coastal habitats and possess tough, flexible cell wall polymers (like alginates) for resistance against wave energy.

2.2. Thallus organization in macroalgae

In complex macroalgae (brown and red Algae), the thallus is differentiated into three distinct parts. These structures are analogous to plant organs but are not true organs because they lack the highly differentiated vascular tissues (xylem and phloem) of land plants.

Algal Structure	Analogy	Primary Function
Holdfast (Crampon / Disc)	Root	Mechanical fixation only; provides anchoring to the substrate (rock, sand) and performs no significant absorption.
Stipe	Stem	Support and connection; elevates the blade toward sunlight. May contain simple conducting cells (sieve tubes) for sugar transport, which are structurally unique from plant phloem.
Blade (Fronde / Lame)	Leaf	Photosynthesis and Absorption. Functions as the primary site for light capture and the absorption of all necessary nutrients, water, and gases.

2.3. Types of cellular organization

Algae exhibit a variety of strategies for forming multi-celled bodies:

- Unicellulaire (e.g., *Chlamydomonas*): The simplest life form; all functions contained within one cell.
- Colonial (e.g., *Volvox*): Cells aggregated into groups, showing minimal functional specialization without true tissue formation.
- Filamentous (e.g., *Spirogyra*): Cells aligned in simple or branched threads, efficient for maximizing exposure to water flow.
- Lamellar (Foliaceous, e.g., Ulva): A flat, sheet-like thallus that maximizes surface area for light capture in two dimensions.
- Cladomothallus (e.g., Batrachospermum): A highly complex, dense structure (typical of some red Algae) based on a central filament and intricate lateral branches.

3. Reproductive cycle of algae (sexual and asexual)

Algal survival relies on the strategic alternation between asexual multiplication and sexual reproduction to ensure rapid growth and genetic fitness.

3.1. Asexual reproduction

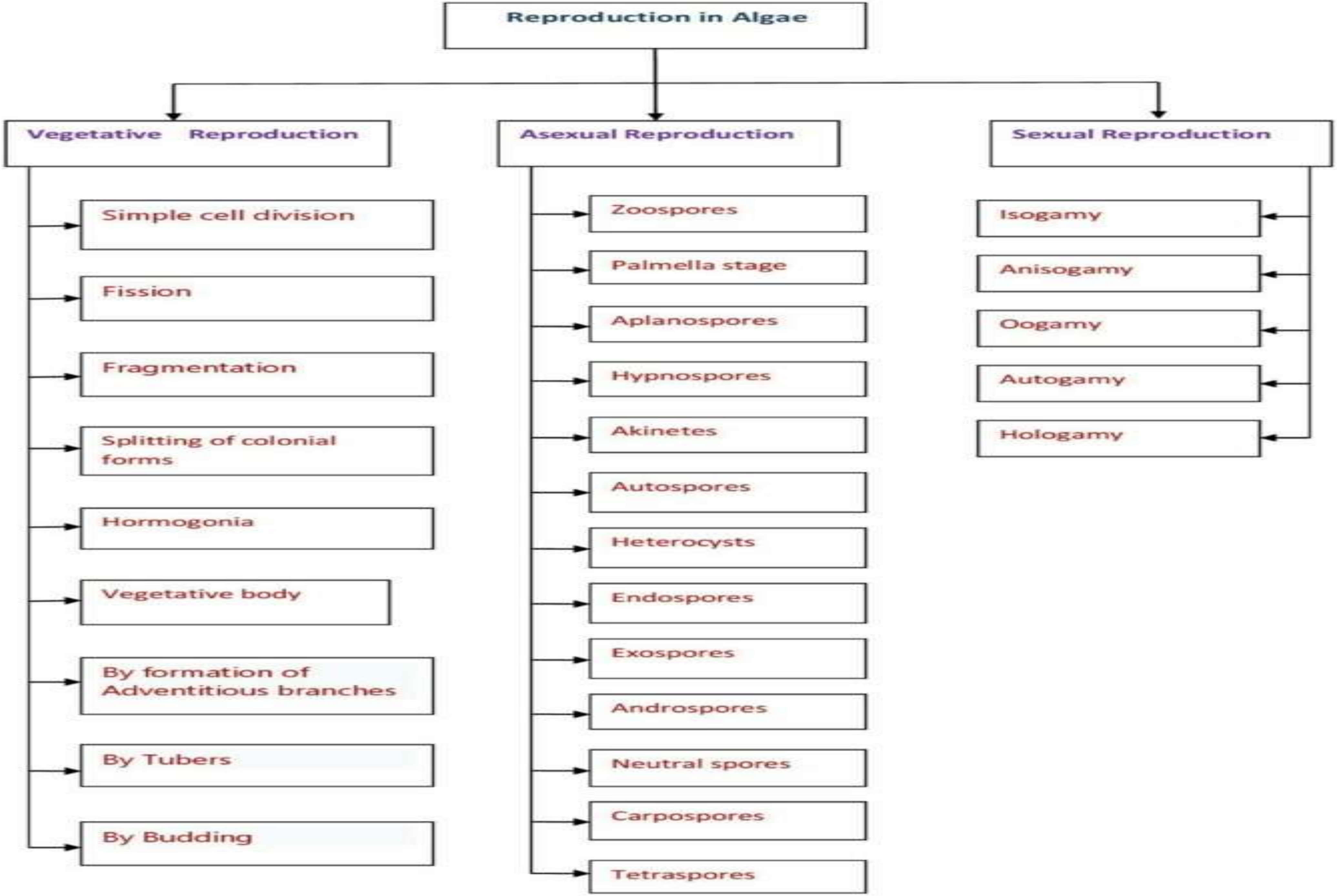
- Cellular Division (Mitosis): Rapid replication in unicellular forms, exemplified by Diatoms forming auxospores to restore maximal size.
- Fragmentation: Propagation in multicellular species where a thallus segment regenerates via totipotency.
- Spore Production (Sporulation): Dispersal via motile Zoospores or non-motile, thick-walled resting cells called aplanospores.

3.2. Sexual reproduction

This process ensures genetic variability via the fusion of haploid gametes (n) to form a diploid zygote (2n).

The principle is the alternation of generations:

Stage	Ploidy	Produced Via	Role
The Gametophyte	Haploid (n)	Mitosis (produces gametes)	Sexual phase
The Sporophyte	Diploid (2n)	Meiosis (produces meiospores)	Dispersal phase



Reproduction in Algae
Vegetative Reproduction
Simple cell division
Fission
Fragmentation
Splitting of colonial forms
Hormogonia
Vegetative body
By formation of Adventitious branches
By Tubers
By Budding
Asexual Reproduction
Zoospores
Palmella stage
Aplanospores
Hypnospores
Akinetes
Autospores
Heterocysts
Endospores
Exospores
Androspores
Neutral spores
Carpospores
Tetraspores
Sexual Reproduction
Isogamy
Anisogamy
Oogamy
Autogamy
Hologamy

Cycles are classified as Monogenetic, Digenetic, or Trigenetic (unique to Rhodophyta). Gamete fusion types are isogamy, anisogamy, or oogamy.

4. Taxonomy of algae

Algae are a polyphyletic assemblage grouped into distinct eukaryotic supergroups based on their pigments, storage compounds, and flagellar features.

- Green Algae (*Chlorophyta*) : Archaeplastida. Possess Chlorophylls a and b; store Starch. Precursors of land plants.
- Brown Algae (*Phaeophyta*) : Stramenopiles (SAR). Pigment is Fucoxanthin; stored carbohydrate is Laminarin. Includes largest algae (Kelp).
- Red Algae (*Rhodophyta*) : Archaeplastida. Use Phycobiliproteins; store Floridean starch. Completely lack flagellated cells.
- Diatoms (Bacillariophyta) : Stramenopiles (SAR). Characterized by the rigid frustule made of biogenic opal silica.
- Dinoflagellates (Dinoflagellata) : Alveolates (SAR). Defined by two distinct flagella; many form toxic Harmful Algal Blooms (HABs).

5. Importance of algae (harmful and beneficial effects of algae)

-Food (food, agar-agar, POU, additives, etc.)

Algae play a significant role in the food industry, serving various purposes such as direct consumption, dietary supplementation, and providing high-value functional ingredients.

For nutritional superfoods, whole macroalgae are especially renowned for their exceptional health benefits. Brown algae varieties, including Kombu and Wakame, and red algae like Nori and Dulse, are particularly valued for their rich nutritional profiles.

- ✓ Minerals and trace elements play a key role by concentrating essential nutrients such as iodine, crucial for thyroid health, along with iron, calcium, and magnesium.
- ✓ Vitamins are also abundant, providing significant amounts of B vitamins—including a bioavailable form of B12 in certain species—alongside Vitamin C and fat-soluble vitamins.

- ✓ Polysaccharides, particularly non-digestible dietary fibers like fucoidans and alginates, act as powerful prebiotics that support a healthy gut microbiome.
- ✓ Hydrocolloids and functional additives sourced from structural polysaccharides are prized for their ability to stabilize, thicken, and gel liquids effectively. Agar-agar (E406), derived from red algae varieties such as *Gracilaria* and *Gelidium*, is recognized as the strongest natural gelling agent. It is widely used to enhance the texture of processed foods, desserts, and jellies.
- ✓ Carrageenans (E407) are polysaccharides extracted from red algae species such as *Kappaphycus* and *Chondrus crispus*. They are classified into three main types—kappa, iota, and lambda—all of which are extensively used in food processing. These variants function as stabilizers in dairy items, particularly milk-based products, and serve as effective thickeners in meat products and sauces, delivering consistent texture management.

- ✓ Alginates (E400-E405) originate from brown algae like *Macrocystis* and *Laminaria*. When exposed to divalent cations, such as Ca^{2+}, they form stable gels. Their primary applications include acting as thickeners in salad dressings and providing structural integrity in reformed food products.
- ✓ Single-cell organism (SCO) supplements, derived from cultivated microalgae, are another innovative development. They are processed into highly concentrated nutritional products, offering a sustainable source of essential nutrients.
- ✓ Spirulina (*Arthrospira platensis*) is a type of cyanobacterium renowned for its remarkable protein content, constituting up to 70% of its dry weight, and for its antioxidant pigment, phycocyanin.
- ✓ Chlorella, another microalga, is notable for its high protein content and abundance of chlorophyll. However, its rigid cell walls have led to its promotion as a potential agent for heavy metal chelation.

Astaxanthin, a potent carotenoid antioxidant derived from *Haematococcus pluvialis*, is highly sought after as a leading nutraceutical supplement.

Risk and Detrimental Factors:

Toxin accumulation: The consumption of algae poses risks due to the potential presence of toxins from Harmful Algal Blooms (HABs). Toxic compounds like domoic acid and saxitoxins can accumulate in shellfish, resulting in severe neurological conditions in humans such as paralytic or amnesic shellfish poisoning.

Heavy metal bioaccumulation: Algae have a natural ability to absorb and concentrate heavy metals from their environment, sometimes reaching levels thousands of times higher than those in the surrounding water. This includes toxic substances such as inorganic arsenic, lead, and cadmium. If algae are harvested from uncontrolled or contaminated sources, they may present significant health risks.

-Pharmaceutical industry (capsules, carrageenans, etc.)

The pharmaceutical industry increasingly recognizes the marine environment's vast biodiversity as a pivotal source for the discovery of new drug candidates, commonly referred to as pharmacophores. Among marine organisms, algae have emerged as a valuable resource in the development of novel therapeutics due to their ability to produce diverse secondary metabolites with significant bioactive properties.

A notable area of drug development driven by algae is centered on bioactive compounds, which have been demonstrated to exhibit a wide range of therapeutic activities:

Antioxidant properties: Secondary metabolites derived from algae, such as high-molecular-weight phenolics like phlorotannins sourced from brown algae, including Ecklonia, and carotenoids such as fucoxanthin, play a critical role in neutralizing reactive oxygen species (ROS) and reactive nitrogen species (RNS).

These compounds offer potential protection against oxidative stress-induced chronic conditions, including neurodegeneration and systemic inflammation.

Anti-inflammatory effects: Algal-derived compounds such as fucoidans, which are sulfated polysaccharides from brown algae, along with specific peptides, exhibit the ability to modulate inflammatory pathways. By suppressing pro-inflammatory signaling molecules such as interleukin-6 and tumor necrosis factor-alpha (TNF-α), these bioactive substances contribute to the attenuation of inflammation.

Antimicrobial and antiviral applications: Various halogenated compounds, such as acetogenins and terpenes, as well as alkaloids and polysaccharides extracted from algae, display inhibitory activity against a broad spectrum of pathogens. These compounds have shown efficacy in combating viruses, including HIV and herpes simplex virus, and drug-resistant bacterial strains by disrupting processes like adhesion or replication.

Anticancer potential: Algal extracts demonstrate the ability to impede metastasis, inhibit angiogenesis, and trigger apoptosis in cancerous cell lines, offering a foundation for innovative cancer therapies.

Gelling and encapsulation agents: Carrageenans play an essential role in the production of vegetarian soft-gel capsules, acting as effective binders or disintegrants in tablet formulations.

Alginate microspheres: Alginates are capable of encapsulating delicate materials such as proteins, enzymes, or cells. This makes them ideal for applications in targeted drug delivery systems or cell transplantation, such as pancreatic islet cells.

-Industry (cosmetics, textiles, gels, etc.)

Cosmeceuticals and dermatology: Algae extracts are highly prized as key ingredients in cosmetic products due to their multifunctional benefits.

- Moisturizing and anti-aging: Polysaccharides such as alginates and fucoidans form a protective barrier on the skin, reducing moisture loss. Rich in vitamins, trace minerals, and potent antioxidants, they enhance skin elasticity and combat the effects of photo-aging.

- Photoprotection: Certain phenolic compounds and pigments found in algae act as natural UV filters while also inhibiting matrix metalloproteinase (MMP) enzymes, which are responsible for collagen breakdown.

Textiles and biomedical materials:

- Alginate fibers: Alginates can be processed into biodegradable, non-woven fibers with excellent absorbency and calcium ion exchange properties. These characteristics make them highly suitable for advanced medical uses, particularly as wound dressings for injuries with significant fluid discharge, such as ulcers or burns.

Gels and thickening: Alginates play a crucial role in altering flow properties and rheology in ceramics and paints, while also functioning as effective suspending agents in industrial slurries.

Environmental Biotechnology and Bioenergy:

- Bioremediation: Algae are utilized in regulated systems to remove surplus nutrients like nitrogen and phosphorus, as well as heavy metals from industrial wastewater. Additionally, they contribute to carbon capture by absorbing CO_2 directly from the atmosphere. Biofuels derived from microalgae have garnered significant attention due to the species' capacity for high lipid concentrations, which can be processed into biodiesel and biojet fuel. These developments highlight a pivotal trajectory in sustainable energy solutions.

Marine mucilage, commonly known as "sea snot," refers to the excessive buildup of a sticky organic substance excreted by phytoplankton. This occurrence is often linked to factors like nutrient pollution from eutrophication and increasing water temperatures.

The resulting mucilage creates dense, blanket-like formations that either float on the surface or sink to the ocean floor. These obstructions can suffocate marine ecosystems by smothering benthic organisms like corals and sponges, while also blocking sunlight, which disrupts photosynthesis in underwater plants.

Hypoxia and anoxia represent critical environmental consequences stemming from the bacterial decomposition of extensive mucilage blooms. This process requires substantial amounts of dissolved oxygen, thereby leading to the formation of regions characterized by hypoxic or anoxic conditions. These zones severely disrupt marine ecosystems, often causing widespread mortality among fish and other aquatic organisms.

Mucilage effectively traps and concentrates bacteria and viruses, including various pathogenic species, often reaching concentrations 1,000 to 10,000 times higher than the surrounding water. This heightened concentration can significantly increase the prevalence of marine diseases.

Even in cases where blooms are non-toxic, the overwhelming accumulation of decomposing biomass can deplete oxygen levels in localized areas, leading to severe ecological instability and disruption.