In 2019, a comprehensive phylogenetic study based on the genomes and transcriptomes of **1,153 plant species** was conducted. This study provided valuable insights into the **evolutionary relationships** among different plant groups.

One notable aspect of this phylogeny was the placement of **algal groups**, which was supported by the genome sequencing of **Mesostigmatophyceae** and **Chlorokybophyceae**.

Interestingly, the analysis revealed that both **"chlorophyte algae"** and **"streptophyte algae"** were treated as **paraphyletic groups**. This means they do not form distinct **monophyletic clades**, as traditionally assumed. The presence of **paraphyletic groups** suggests that the **evolutionary relationships** among these organisms are more complex than previously thought.

Additionally, the classification of **Bryophyta**, which includes **mosses, liverworts, and hornworts**, was supported by the 2019 study and **phylogenetic analyses** involving the genome sequencing of hornworts. This confirmed the evolutionary connections of these **non-vascular plants** and their position within the plant kingdom.

Overall, advancements in **genome sequencing** and **phylogenetic analysis** have significantly improved our understanding of **plant evolution and taxonomy**.

g) Plant diversity (wikipédia)

Diversity of living green plant (Viridiplantae) divisions by number of species

Informal group	Division name	Common name	No. of described living species
Green algae	Chlorophyta	Green algae (chlorophytes)	3800–4300 [21][22]
Green algae	Charophyta	Green algae (e.g. desmids & stoneworts)	2800–6000 [23][24]
Bryophytes	Marchantiophyta	Liverworts	6000–8000 [25]
Bryophytes	Anthocerotophyta	Hornworts	100–200 [26]
Bryophytes	Bryophyta	Mosses	12000 [27]
Pteridophytes	Lycopodiophyta	Clubmosses	1200 [28]
Pteridophytes	Polypodiophyta	Ferns, whisk ferns & horsetails	11000 [28]
Spermatophytes (seed plants)	Cycadophyta	Cycads	160 [29]
Spermatophytes (seed plants)	Ginkgophyta	Ginkgo	1 [30]
Spermatophytes (seed plants)	Pinophyta	Conifers	630 [28]
Spermatophytes (seed plants)	Gnetophyta	Gnetophytes	70 [28]
Spermatophytes (seed plants)	Angiospermae	Flowering plants	258650 [31]

I. Rhodophytes (Rhodophyta) ; Red algae

Red algae (**division Rhodophyta**) include **over 7,000 species** of predominantly marine algae, often found attached to rocks, other algae, or coastal plants. Their morphological range includes **unicellular, filamentous, branched, feathery, and blade-like (leaf-shaped) thalli**. The taxonomy of this group is controversial, and the organization of the Rhodophyta division may not accurately reflect the **phylogeny (evolutionary relationships)** of its members.

Updated Classification of Rhodophyta

Traditionally grouped into a single class (**Rhodophyceae**), modern classifications now recognize at least two major classes:

- **Bangiophyceae** – Simple, mostly unicellular or filamentous red algae (e.g., *Porphyra*).
- **Florideophyceae** – Multicellular, complex red algae with pit connections and a triphasic life cycle (e.g., *Corallina, Polysiphonia, Chondrus crispus*).

Some classifications also propose additional minor classes, such as **Compsopogonophyceae** and **Stylonematophyceae**.

1. Morphology

1.1 Pigmentation

Rhodophytes contain pigments found in other plants, such as **chlorophyll a** and **carotenoids** (e.g., lutein and zeaxanthin). However, their uniqueness lies in the presence of **phycobilisomes**, which contain **phycobiliproteins**: **allophycocyanin (blue), phycocyanin (blue), and phycoerythrin**, which gives them their characteristic red color by absorbing blue-green light. The chloroplast in red algae is therefore referred to as a **rhodoplast**.

The **organization of the chloroplast** is as follows:

- **Thylakoids are free and do not form grana** due to the presence of **phycobilisomes** on their surface.
- They are arranged **concentrically within the chloroplast** and fill most of the internal space.
- Unlike **Glaucophytes**, which retain a **peptidoglycan layer** around their chloroplasts, and **Cyanobacteria**, which also have free thylakoids but a different internal arrangement, red algae have a more specialized plastid structure adapted for their marine environment.

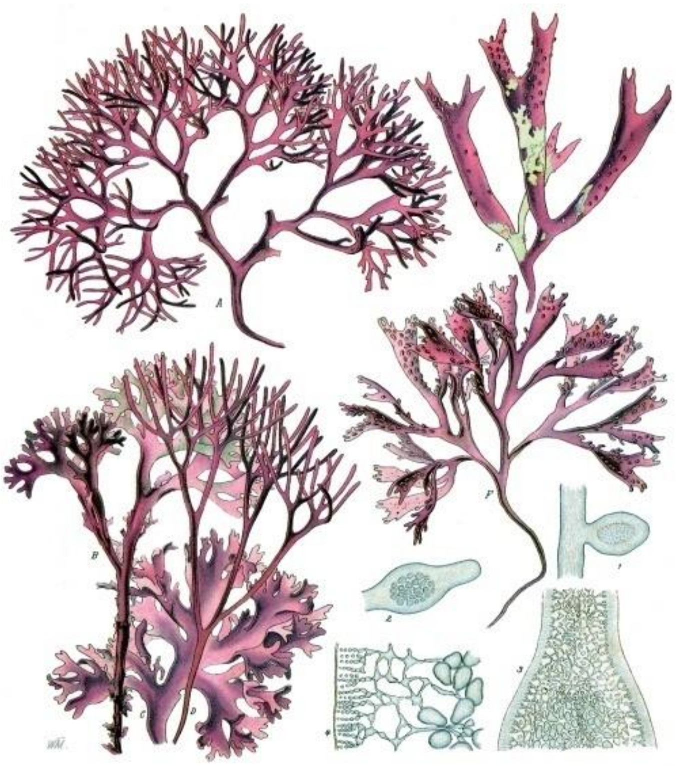

Figure 5.3: Different forms of two red algal species: *Chondrus crispus* and *Gigartina mamillosa*. The letters A, B, C, and D represent different forms of *Chondrus crispus*, while the letters E and F represent forms of *Gigartina mamillosa*. The numbers 1 to 4 depict transverse and longitudinal sections of thallus parts and cystocarps of these algae, enlarged for better observation.

Köhler's Medizinal-Pflanzen

The pigmentation (**ratio of present pigments**) is remarkably influenced by the **wavelength of light** that reaches the alga. In deeper waters, algae accumulate a high amount of **phycoerythrin**, a pigment capable of absorbing light at those depths. Conversely, when algae grow near the surface, the amount of this **red pigment decreases**, making them appear **greener** despite their classification as red algae. However, the **chlorophyll content remains unchanged**, regardless of depth. This phenomenon is known as **chromatic adaptation**.

1.2 Cellular organization

Red algae have **double-layered cell walls**. The **outer layers** contain the polysaccharides **agarose** and **agaropectin**, which can be extracted from the cell walls as **agar** by boiling. The **inner walls** are primarily composed of **cellulose**, and in some species, such as **Corallinales**, they also contain **calcium carbonate**, providing additional structural support.

Plastid Genome

The **plastid genomes of red algae** are among the **most gene-rich** known, containing numerous genes related to **photosynthesis and metabolism**.

Cellular Structure of Red Algae

Red algae **lack flagella and centrioles** throughout their entire life cycle. Distinctive features of their cellular structure include:

- **Spindle fibers and microtubules** involved in cell division.
- **Unstacked thylakoid membranes** containing **phycobilisome pigment granules** (phycobilins).
- **Pit connections** between cells, facilitating intercellular communication.
- **Filamentous growth forms** in many species.
- **Absence of a chloroplast endoplasmic reticulum (ER)**, unlike in some other algal groups.

Storage Compound

Red algae store starch in the **cytoplasm as floridean starch** (*rhodamylon*), rather than inside plastids as in **plants and green algae**. Structurally, **floridean starch is more similar to glycogen** than to true plant starch.

1.3 Ecology

Red algae, or **rhodophytes**, are **marine organisms** found in a variety of habitats, ranging from **rocky shores** to **coral reefs**. They play a **crucial ecological role**, providing **habitat, food, and protection** for many marine species. Some red algae are particularly abundant in coral reefs, such as the **Corallinaceae**, which produce an **extracellular calcium carbonate layer** and contribute to **reef formation**.

Certain red algae are highly **resistant to extreme conditions**, making them **extremophiles**. For example, *Cyanidium caldarium* thrives in **acidic hot springs** with a **pH below 1**.

Chondrus crispus and *Mastocarpus stellatus* (*Gigartina stellata*) are **rock-attached species** often found together. These species are harvested for their **carrageenan**, a gelling agent widely used in the **food industry**.

Agar-agar is a **galactose-based polymer (galactan)** found in the **cell walls** of certain red algae, particularly those from the **Gelidiaceae** (*Gelidium*, *Pterocladia*) and **Gracilariaceae** (*Gracilaria*) families. Agar-agar has **numerous applications**, including **cooking and biological research techniques**.

1.4 Life cycle

☞ *Asexual reproduction*

Asexual reproduction in red algae can occur through **spore production** and **vegetative methods**, such as **fragmentation, cell division, or propagule formation**.

In some **Bangiophycidae**, reproduction occurs **exclusively through vegetative means**, where the **thallus fragments into isolated cells**. In other species, as well as in certain **Florideophyceae**, asexual reproduction can occur **independently of the sexual cycle**, through **mitotic spores** (*monospores and paraspores*), which develop directly into a new generation identical to the parent.

☞ *Sexual reproduction*

Most **gametophytes** in red algae are **dioecious** (separate male and female individuals). The **female cell** (*carpogonium*) does not release gametes; instead, it **remains attached** to the gametophyte and has a specialized structure to facilitate fertilization—a **papilla** in **Bangiophycidae** or a **long hair-like projection called a trichogyne** in **Florideophyceae**.

In some species, such as **Acrochaetiales**, the carpogonium develops from a **transformed vegetative cell** of the thallus. However, more commonly, it is located at the tip of a **short adventitious branch**, typically composed of **two to five cells**, called the **carpogonial branch**. In **Cryptonemiales** (*Dudresnaya*), this branch is further supported by a specialized structure known as the **carpogonial gonophore**, which plays an essential role in **zygote development**.

Male Gamete Formation and Fertilization

- In **Bangiophycidae**, **male gametes** arise from the **repeated division** of a **vegetative cell** into **small, colorless cells**, which are released when the **cell walls dissolve into a gel-like substance**.
- In **Florideophyceae**, **male cells** form **individually inside spermatocysts**, often grouped in clusters (*e.g., Polysiphonia*).

In all cases, **male gametes** (*spermatia*) are **small, immobile, and lack a cell wall**. They are **passively transported** by **water currents** toward a **trichogyne**, where one adheres and releases its contents. The **male nucleus then fuses with the female carpogonium nucleus**, completing fertilization.

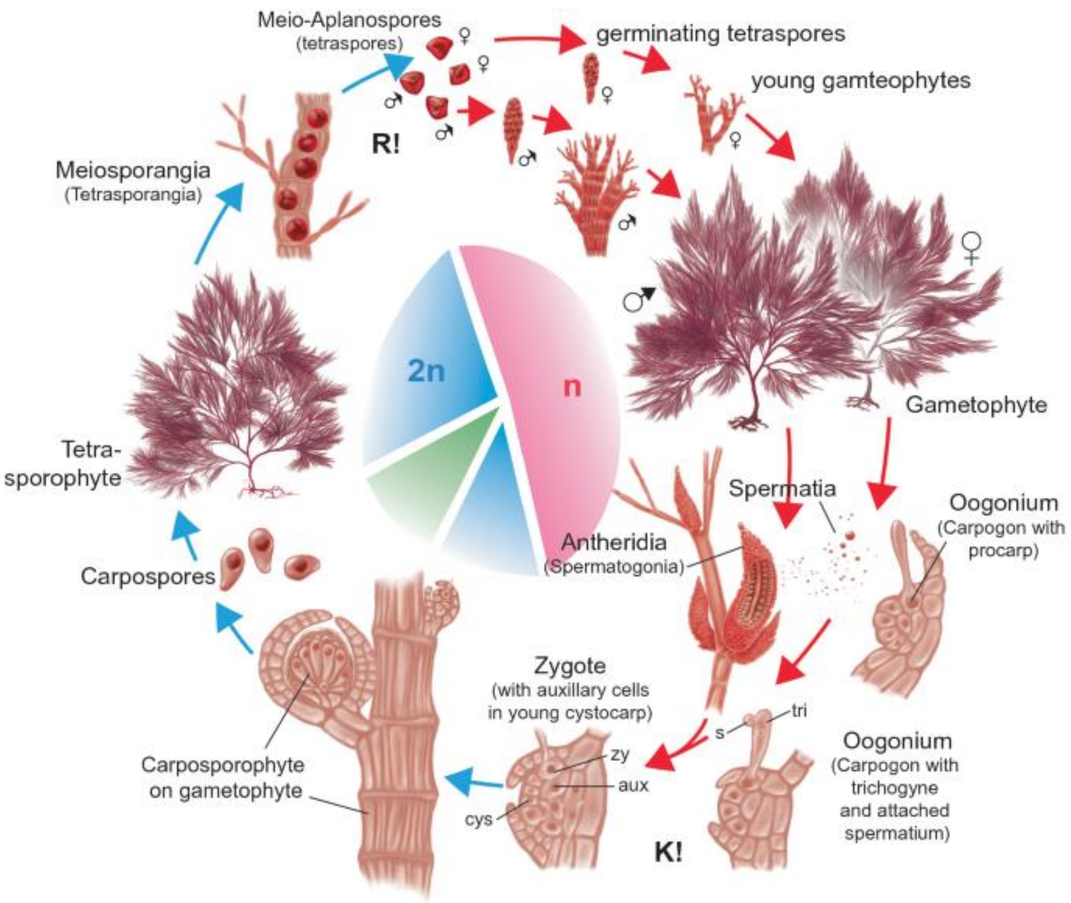

Figure 5.4: Sexual reproduction in Rhodophytes

☞ Zygote Development: The Carposporophyte

The zygote, formed from the fertilized carpogonium, remains attached to the gametophyte. In *Porphyra*, it divides into multiple spores (*carpospores*), which are then released. In **Florideophyceae**, the zygote develops into a diploid tissue called the **gonimoblast**, which produces carpospores, representing a distinct generation known as the **carposporophyte**.

In **lower Florideophyceae**, the carposporophyte consists of **cells with pigmented plastids** and is **not entirely parasitic**. However, in more evolved forms, the carposporophyte, which initially **lacks assimilatory pigments**, becomes an **obligate parasite** of the gametophyte. This parasitism is particularly evident in the **fusion of filaments derived from the diploid zygote** with specialized gametophyte cells. The **host cells**, which accommodate the **parasitic diploid nucleus**, are known as **auxiliary cells**. These cells support the multiplication of the nucleus, eventually leading to the formation of **clusters of carpospores**.

☞ ***Trigenetic cycle***

The **trigenetic cycle** in red algae involves three distinct generations:

a. **Gametophyte (haploid, n)** – Produces male and female gametes.
b. **Carposporophyte (diploid, 2n)** – Develops from the zygote and remains attached to the female gametophyte, producing diploid carpospores.

c. **Tetrasporophyte (diploid, 2n)** – Develops from carpospores and undergoes meiosis to produce haploid tetraspores, which then grow into new gametophytes.

This alternation of generations is characteristic of **Florideophyceae**.

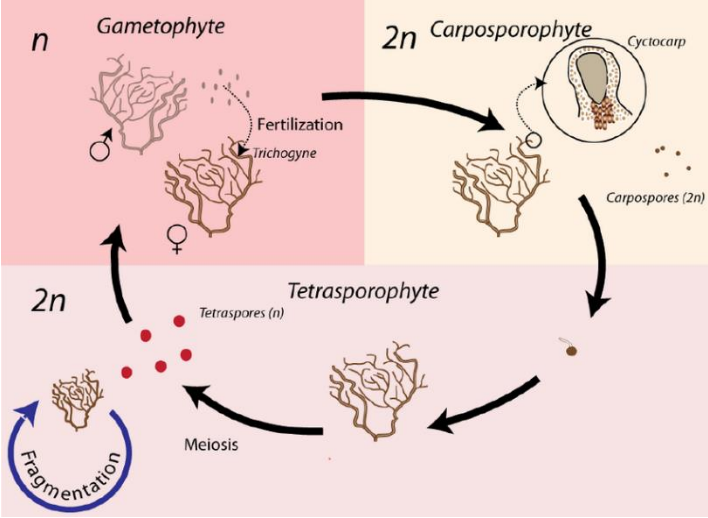

Figure 5.5: Summary of Kappaphycus and Eucheuma life cycles.

2. *Glaucophytes*

Glaucophytes are unicellular eukaryotic organisms belonging to a group of freshwater algae with low diversity. They are mainly found in environments such as lakes, ponds, or marshes, primarily in freshwater ecosystems, though not necessarily restricted to temperate regions. They form an integral part of the microbial community in these habitats.

Figure 5.6: *Glaucocystis* sp. under microscope.

Their cellular organization varies among species. Some, like *Cyanophora paradoxa*, possess two flagella of unequal lengths, while others, such as *Glaucocystis*, are non-motile and lack flagella. The chloroplasts, known as cyanelles, are distinguished by their blue-green coloration due to the presence of accessory pigments—namely phycocyanin and allophycocyanin grouped in phycobilisomes. A notable feature of cyanelles is the retention of a peptidoglycan wall, a vestige of their cyanobacterial origin.

Reproduction occurs exclusively asexually. In flagellated forms, division is carried out by longitudinal binary fission, while in non-motile (capsaline and coccoid) forms, multiplication occurs through the formation of multiple daughter cells. To date, no mode of sexual reproduction has been reported.

Currently, about 14 species of glaucophytes, including the emblematic model Cyanophora paradoxa, have been described and are recognized, although new discoveries and taxonomic revisions may further refine this classification.

3. *Green algae*

Green algae are a group of autotrophic eukaryotes containing **chlorophyll a and b**, encompassing the phyla **Chlorophyta** and **Streptophyta**. They exhibit a wide range of morphological diversity, including **unicellular flagellates and non-flagellated forms, colonial, coccoid, filamentous, and multicellular macroalgae**. Most flagellated species possess **two flagella per cell**, although some lineages have lost them during evolution.

There are approximately **22,000 described species** of green algae. Many exist primarily as **unicellular forms**, while others form **coenobia (structured colonies), long filaments, or highly differentiated macroalgae**. Some species have complex multicellular structures with specialized cells, such as those found in *Ulva* (sea lettuce) or *Caulerpa*, which exhibit **tissue-like organization despite being coenocytic (multinucleated and not divided into separate cells).**

Green algae **do not form a single monophyletic clade** because **Chlorophyta and Streptophyta are not more closely related to each other than they are to other photosynthetic eukaryotes**. Instead, they form a **paraphyletic group**, as the **Streptophytes include the charophyte algae, which share a common ancestor with land plants** (*Embryophytes*). This means that land plants evolved from within the green algal lineage.

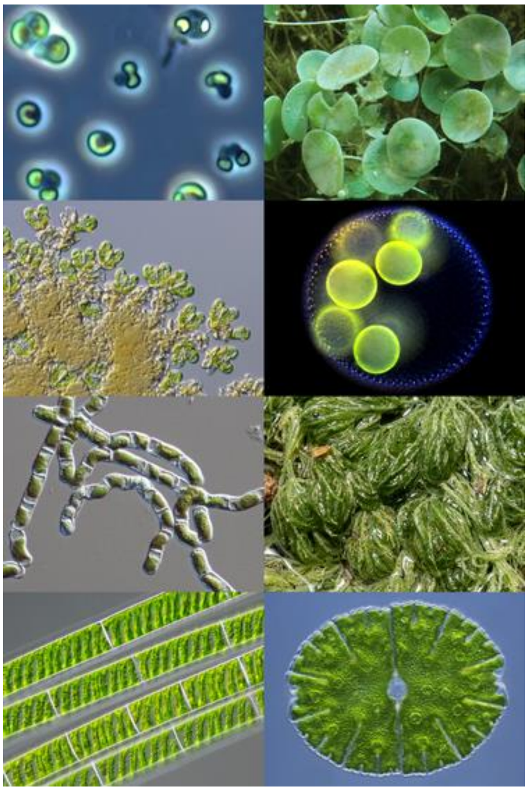

Fig 5.7a : Green algal diversity. From top left corner: *Picocystis* (Picocystophyceae), *Acetabularia* (Ulvophyceae), *Botryococcus* (Trebouxiophyceae), *Volvox* (Chlorophyceae), *Klebsormidium* (Klebsormidiophyceae), *Chara* (Charophyceae), *Spirogyra* and *Micrasterias* (Zygnematophyceae)

Green algae are primarily **aquatic**, thriving in **freshwater, marine, and even terrestrial habitats** (such as soil, tree bark, or symbiotic relationships with fungi in lichens). Some species, like *Chlamydomonas nivalis*, can even survive in **extreme environments**, such as snowfields and glaciers, giving rise to the phenomenon of **"watermelon snow"** due to their red carotenoid pigments.

The **origin and diversification** of major green algal lineages remain an active area of research, with fossil evidence suggesting their emergence over **1 billion years ago**.

3.1 Cellular structure

Green algae have **chloroplasts** containing **chlorophyll a and b**, which give them their characteristic bright green color. They also possess **accessory pigments**, including **β-carotene (red-orange) and xanthophylls (yellow),** which are embedded in **stacked thylakoids** within the chloroplasts.

The **cell walls** of green algae are **primarily composed of cellulose**, and they store carbohydrates in the form of **starch**, similar to land plants.

All green algae have **mitochondria with flat cristae**, a feature that distinguishes them from some other eukaryotic groups. When present, their **paired flagella** are used for cell movement and are anchored by a **cross-shaped system of microtubules and fibrous filaments**, which plays a role in flagellar coordination.

3.2 Reproduction

Unicellular green algae can reproduce **both asexually and sexually**, depending on environmental conditions.

☞ ***Asexual Reproduction***

- The most common mode of reproduction in unicellular algae.
- Occurs via **binary fission**, where the parent cell divides into two identical daughter cells.
- Some species undergo **multiple fission**, producing **4, 8, or more daughter cells** within the parental cell wall before being released (e.g., *Chlamydomonas*).
- **Autospore formation** occurs in non-motile species (e.g., *Chlorella*), where daughter cells develop inside the parent cell before being released.

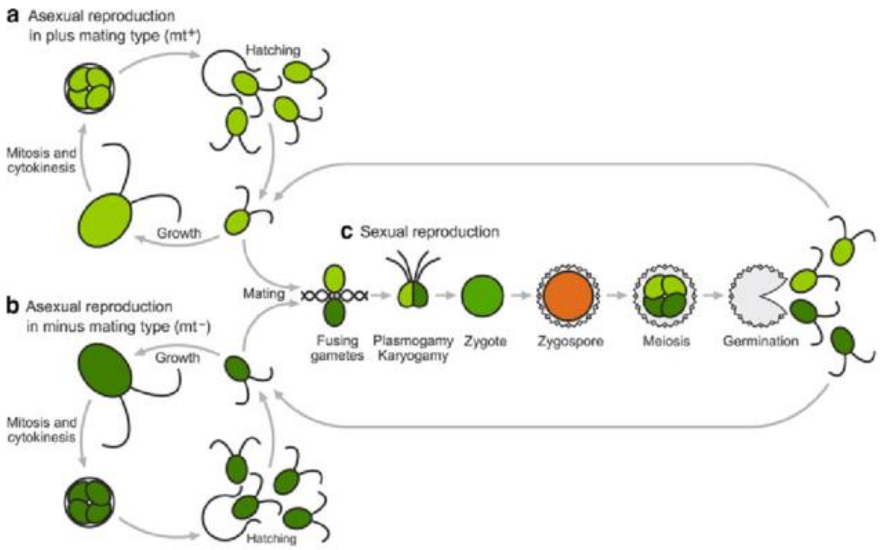

Fig 5.7b: Asexual and sexual reproduction in *C. reinhardtii*. Under favorable conditions of growth, *Chlamydomonas* reproduces asexually; only when the conditions are unfavorable does it reproduce sexually.

☞ ***Sexual Reproduction***

Green algae are a group of **photosynthetic, eukaryotic organisms** that exhibit **both haplobiontic and diplobiontic life cycles**. In **diplobiontic species**, such as *Ulva*, reproduction follows an **alternation of generations**, where two multicellular forms—**haploid (gametophyte) and diploid (sporophyte)**—alternate (figure 5.7c). These forms can be either **isomorphic** (identical in morphology) or **heteromorphic** (different in size and structure).

In **haplobiontic species**, only the **haploid gametophyte** is multicellular. After fertilization, the **diploid zygote** undergoes **meiosis**, producing haploid cells that develop into new gametophytes. In contrast, **diplobiontic forms**, which evolved from haplobiontic ancestors, have both **a multicellular haploid gametophyte and a multicellular diploid sporophyte**. In these species, the **zygote undergoes mitotic divisions** to form a **sporophyte**, which later produces **haploid spores via meiosis**. These spores germinate into new gametophytes.

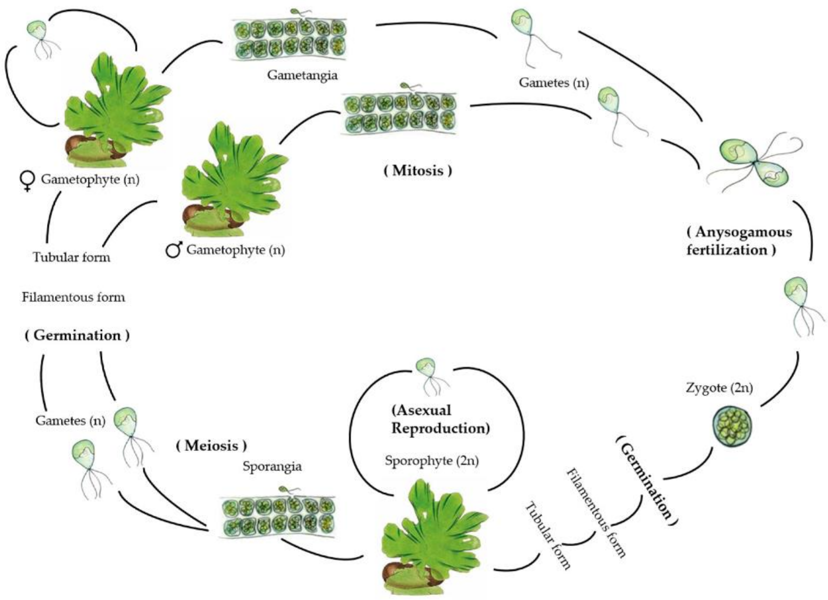

Figure 5.7c: *Ulva lactuca* life cycle.

All land plants share a **diplobiontic ancestor**, and **alternation of generations** has also evolved independently multiple times within **Ulvophyceae**, as well as in **red and brown algae**.

Morphological Diversity in Diplobiontic Green Algae

Diplobiontic green algae can be either:

- **Isomorphic**, where the **haploid and diploid generations have identical morphology**. (e.g., *Chlamydomonas reinhardtii*) (figure 5.7b).
- **Heteromorphic**, where **the gametophyte and sporophyte differ in size and form**.

Modes of Reproduction

Green algae exhibit diverse reproductive strategies, ranging from:

- **Isogamy** – fusion of morphologically identical gametes.
- **Oogamy** – fertilization of a **large, non-motile egg** by a **smaller, motile sperm**.
- **Conjugation** – a form of sexual reproduction where **haploid cells fuse through cytoplasmic bridges**, as seen in filamentous algae like *Spirogyra*. This process leaves behind **distinct empty cell walls**, which can be observed under a light microscope.

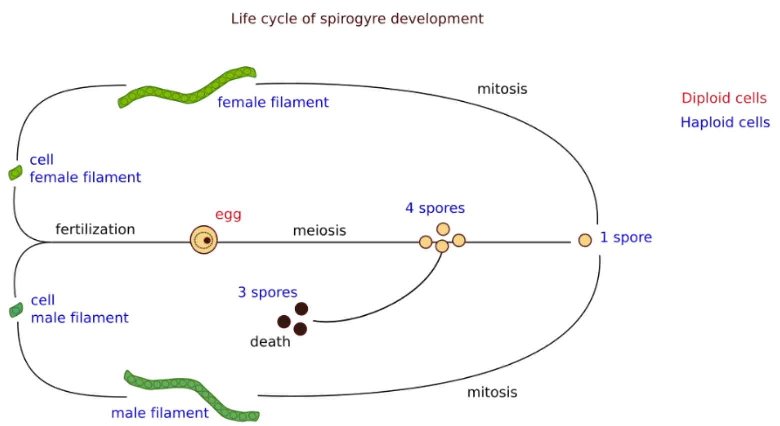

Figure 5.8: Haplophasic monogenetic life cycle.

3.3 Habitats and Ecological Roles of Green Algae

❖ ***Aquatic Habitats***

Green algae are widely distributed in **aquatic environments**, including:

- **Freshwater ecosystems**: lakes, rivers, ponds, marshes, and reservoirs.
- **Marine ecosystems**: coastal waters, estuaries, intertidal zones, and coral reefs.
- **Extreme environments**: Some species, such as *Chlamydomonas nivalis*, thrive in **glacial environments**, while others survive in **hot springs, brackish waters, and hypersaline lakes**.

Some unicellular and colonial green algae, such as *Volvox*, are **planktonic**, freely floating in water, while others, like *Ulva* (sea lettuce), are **benthic**, attaching to surfaces like rocks, shells, or coral reefs.

❖ ***Terrestrial Habitats***

Although predominantly aquatic, some green algae are well adapted to terrestrial environments, colonizing:

- **Soil, tree bark, and rock surfaces**, often forming **biofilms** in humid conditions.
- **Epiphytic habitats**, growing on other plants, particularly in rainforests and humid regions.
- **Desert and polar environments**, where some species survive by forming **cryptobiotic crusts**, entering a dormant state during droughts.
- **Pioneer species**: Some green algae are among the first organisms to colonize barren or disturbed landscapes, playing a role in **soil formation and ecological succession**.

❖ ***Symbiotic Associations***

Green algae engage in **various mutualistic relationships**, including:

- **Lichens**: Symbiosis with fungi, forming lichens, which are critical for soil formation in harsh environments.
- **Endosymbiosis with animals**: Found in **cnidarians (e.g., Hydra), flatworms (Platyhelminthes), and mollusks**, where they provide photosynthetically derived nutrients.
- **Coral symbiosis**: Some green algae, like *Ostreobium*, live **inside coral skeletons**, aiding reef resilience.
- **Protozoan hosts**: Some single-celled algae live **inside protozoa**, forming endosymbiotic relationships.

❖ ***Ecological Roles***

Green algae play **key ecological functions** across multiple ecosystems:

- **Primary producers**: Essential in **both freshwater and marine food chains**, supporting herbivores and filter feeders.
- **Oxygen production**: As **photosynthetic organisms**, they contribute to atmospheric oxygen through **oxygenic photosynthesis**.
- **Nutrient cycling**: Involved in **carbon and nitrogen fixation**, particularly in symbiosis with bacteria.
- **Water purification**: Some species aid in **wastewater treatment**, absorbing excess nutrients and pollutants.
- **Bioindicators**: Their presence or absence serves as an indicator of **water quality, pollution levels, and climate change effects**.