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Review Article

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Algal Symbiosis to the Ecological Success of Angiosperms

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Abstract

The success of angiosperms (flowering plants) is heavily reliant on their partnerships with algae, a crucial, yet often underestimated, form of symbiotic interaction. This review delves into the complex relationships between angiosperms and algae, highlighting the various types, processes, and ecological significance of these symbiotic bonds. It first examines the different forms of algal symbiosis—including endosymbiosis, epiphytic symbiosis, cyanobacterial symbiosis, and photo symbiosis—each playing a unique role in the plant's physiological and ecological processes. The discussion then moves to the molecular and cellular mechanics that underpin these partnerships, emphasizing the critical interdependencies and nutrient exchanges that sustain them. Furthermore, we analyzed the genetic control of these symbioses, showcasing the precise genes and pathways involved in their initiation and maintenance. This detailed analysis underscores the vital role algal symbiosis plays in enhancing angiosperms' adaptation, particularly in challenging environments, and offers broader insights into the connections within ecology and evolution.

Keywords: Angiosperms, Algal Symbiosis, Endosymbiosis, Epiphytic Symbiosis.

1. Introduction

Symbiosis—the close association of two different organisms, usually for mutual benefit[1] is a foundational concept in biology, essential for the survival and evolution of diverse species, from fungi and microbes to plants and mammals. Broadly, symbiosis encompasses a spectrum of relationships, ranging from parasitism (where one organism benefits to the detriment of the other) to mutualism (where both parties benefit[2]. Mutualistic symbiosis within plants is of particular interest, involving intricate and specialized interactions that profoundly influence the fitness and ecology of the participating species. Symbiotic interactions are fundamental to a plant kingdom, as they are prerequisites for nutrient uptake, resistance to environmental stressors, and overall plant health[3]. While this symbiotic connection is most famously known through the partnership between legumes and nitrogen-fixing bacteria—which convert atmospheric nitrogen into a usable form, boosting plant development in nitrogen-poor soils—most plant roots also form symbiotic associations with mycorrhizal fungi. These fungi assist plants in absorbing vital water and minerals, such as phosphorus, in exchange for carbohydrates produced by the plant during photosynthesis[4]. Another fascinating area of plant symbiotic interactions, less well known, however, is algal symbiosis in angiosperms.

Algae live inside tissue of flowering plants and supply energy and nutritional needs, particularly under conditions of nutrient scarcity[5]. This connection may be vital for the survival of the plant, more so in harsh environments with limited access to conventional ways of acquiring nutrients. Research into the angiosperm algal symbiosis provides information on the broader ecological and evolutionary effects of symbiosis within the plant kingdom, other than shedding light on adaptive mechanisms of these plants.

2. Types of Algal Symbiosis

2.1 Endosymbiosis

Endosymbionts are prokaryotic cells that reside within eukaryotic cells. The term *endosymbiosis* refers to the living of two organisms, one inside the other[6]. The word *endosymbiont* originates from Greek—*endo* meaning "inside" and *symbiosis* meaning "living together," where *syn* means "with" and *bios* means "life."

The theory of endosymbiosis explains that the evolution of algae and chloroplasts occurred through a series of such events. Initially, a prokaryotic cell was engulfed by a eukaryotic cell, resulting in the earliest case of endosymbiosis. Through this **primary endosymbiosis**, mitochondria were formed. Later, chloroplasts are believed to have originated when photosynthetic cyanobacteria were ingested by a mitochondria-containing eukaryotic cell[7].

Chloroplasts arising from primary endosymbiosis are surrounded by two membranes—one from the host and another from the endosymbiont. Green and red algae acquired their chloroplasts in this way. In **secondary endosymbiosis**, however, a eukaryotic cell engulfs another cell that had already undergone primary endosymbiosis, leading to chloroplasts surrounded by more than two membranes. The chloroplasts of brown algae are the outcome of this secondary process.

2.2 Epiphytic Symbiosis

Epiphytic algae, though photosynthetic and capable of fixing carbon, often obtain it from their photosynthetic host[8]. This relationship offers algae protection from predators and environmental stresses such as desiccation or excessive light.

An epiphyte is defined as a plant or plantlike organism that grows upon another plant (phorophyte). It derives water and nutrients from rainfall, debris, and the surrounding environment (or seawater in marine systems). Epiphytes contribute to biomass and biodiversity in their habitats and play a vital role in nutrient cycling[9]. They also serve as an important food source for many animals. Older plant structures typically support more epiphytes, thereby increasing food web complexity.

Unlike parasites, epiphytes use their hosts only for structural support and do not harm them[10].

2.3 Cyanobacterial Symbiosis

Cyanobacteria form diverse symbiotic relationships with eukaryotic hosts such as plants, fungi, sponges, and protists. As nitrogen-fixing photoautotrophs, they provide both carbon and nitrogen to their hosts and may also exhibit facultative heterotrophy. These relationships, often termed photosymbiosis, are found in lichens, plankton, ciliates, and numerous marine species including corals, giant clams, and jellyfish[11].

Figure 2: Epiphytic symbiosis (Xu and Wang 2023)[12]

Photosymbiosis has played a major role in ecosystem evolution and stability, contributing to soil formation, microbial diversity, and reef construction. For example, the moss *Plagiomnium affine* displays chloroplast-rich cells due to such associations[13]. These photosymbiotic relationships are thought to have enabled eukaryotes to acquire photosynthesis, ultimately giving rise to plants.

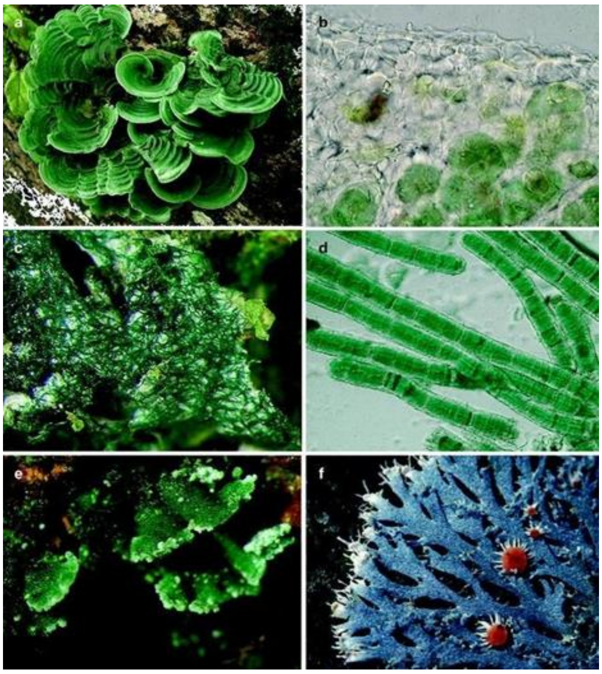

Figure 3: Cyanobacterial Symbiosis

3. Algal Symbiosis Mechanisms in Angiosperms

3.1 Cellular and Molecular Interactions

- **Cellular interactions**: Algae may exist as epiphytes (on surfaces) or endophytes (within tissues). They can bind to plant cells, penetrate tissues, and remain in close contact via specialized structures such as pores or plasmodesmata[14] (Mathesius 2022).
- **Molecular interactions**: Plants and algae exchange signal molecules (e.g., hormones, peptides) that mediate recognition and compatibility through receptor-ligand mechanisms.

3.2 Types of Algal Endosymbionts

- **Green Algae (Chlorophyta)**

Vančurová et al.[15] and Bachy et al.[16] reported in their studies that *Zygnema* and *Cladophora* commonly occur as endosymbionts. The chlorophyll a and b of these algal forms enhance photosynthetic capacity in various plant tissues such as leaves and stems and support overall productivity of those plants.

Figure 4: Green algae (Strullu-Derrien et al. 2018)[17]

- **Cyanobacteria (Blue-Green Algae)**

The genera like *Nostoc* and *Anabaena* establish symbiotic relationship with various plants. Their phycobilisomes absorb light for photosynthesis[18]. These cyanophycean members fix atmospheric nitrogen and provide essential compounds that improve plant growth and health[19].

Figure 5: Cyanobacteria (Blue-Green Algae)

- **Other Algal Groups**

Some red and brown algae also form symbioses. Brown algae (with fucoxanthin pigments) and red algae (with phycoerythrin) can photosynthesize under varied light conditions, allowing plants to adapt to diverse environments[20].

3.3 Characteristics of Algal Endosymbionts

- **Cellular structure**: Specialized organelles such as plastids and thylakoids aid photosynthesis within plant tissues.
- **Photosynthetic adaptation**: Unique pigments help absorb light in shaded environments.
- **Reproductive mechanisms**: Endosymbionts may reproduce asexually inside host tissues or synchronize with host reproduction.

- **Physiological adaptations**: Algae evolve defense strategies against variable conditions in plants (light, temperature, nutrient fluctuations).
- **Metabolic exchange**: They share products with the host—providing photosynthates and nitrogen in return for essential nutrients.

4. Nutrient Exchange and Metabolic Interdependencies

4.1 Nutrient Exchange

Through photosynthesis, algae fix carbon into carbohydrates, which the plant uses for growth, reproduction, and defense[21]. In return, algae obtain nutrients such as nitrogen and phosphorus, essential for metabolic processes[22].

4.2 Metabolic Interdependencies

This mutualism sustains both partners: algae provide carbohydrates to the host, while plants supply amino acids, vitamins, and metabolites that regulate algal growth, enzyme activity, and stress tolerance. Together, they adapt effectively to environmental changes.

4.3 Genetic Regulation of Symbiotic Relationships

- **Genetic control**: Specific genes regulate initiation and maintenance of symbiosis, including those coding for nutrient transporters and signaling proteins.
- **Genetic mechanisms**: Differential gene expression ensures that plants selectively activate or suppress genes to favor beneficial algae.
- **Host-specific adaptations**: Plants evolve recognition mechanisms tailored to their algal partners, reflecting co-evolution.

5. Ecological Roles of Algal Symbiosis in Angiosperms

Algal symbiosis is a vital adaptation that helps flowering plants (angiosperms) thrive, especially in nutrient-poor or stressful environments.

Algal symbiosis is a crucial strategy for angiosperms (flowering plants), particularly in environments with limited resources. This partnership significantly enhances the plant's ability to acquire essential nutrients, which are often scarce in nature. Symbiotic algae perform two key functions: they fix nitrogen from the atmosphere and mobilize phosphorus from otherwise inaccessible sources[23]. These vital nutrients are then passed on to the host plant, resulting in improved growth, vigor, and survival. This is especially beneficial in nutrient-poor soils, allowing angiosperms with algal partners to thrive and dominate, contributing to greater ecosystem productivity by more efficiently utilizing limited resources[24].

Beyond nutrient acquisition, algal symbiosis provides increased tolerance to environmental stress. Angiosperms constantly face challenges like drought, high salinity, and temperature extremes, which can negatively impact their life cycle. Symbiotic algae help mitigate these stressors by maintaining higher water levels near the roots, producing protective compounds, and boosting resistance to oxidative stress. Consequently, this symbiosis allows angiosperms to colonize extreme environments and flourish in a wider variety of ecological niches[25].

A third major ecological benefit is the enhancement of photosynthetic efficiency. Since the symbiotic algae are photosynthetic organisms themselves, they contribute additional energy to the host. They can supply the host plant with glucose directly or help improve the host's own photosynthesis by altering pigmentation and optimizing positioning for maximum light capture. This enhanced efficiency provides a substantial advantage for the host plant. Algal symbiosis provides significant advantages to host plants, manifesting as accelerated growth rates, increased biomass production, and heightened reproductive success. Critically, this symbiotic relationship extends its benefits to the broader environment by enhancing overall ecosystem stability. The competitive superiority often achieved by angiosperms with algal partners subsequently drives greater diversity and productivity within plant communities. By reinforcing ecosystem resilience, especially against climatic stressors and nutrient instability, these interactions are vital for maintaining biodiversity and ensuring long-term ecological balance[26].

Table 1: Research Study Data

Authors	Subject	Result
Raval, MacLeod, and Gould (2023)[27]	Organelle evolution in plants and algae	Identified 31,625 protein families unique to plastid-bearing eukaryotes, showing remodeling of mitochondria and plastids that aided chlorophytes in adapting to land environments.
Soltis, Folk, and Soltis (2019)[28]	Darwin's contributions to evolutionary botany	Darwin's work shaped evolutionary botany, impacting phylogenetics, reproduction, and diversification in angiosperms; highlighted rapid radiations since the Early Cretaceous.
Wang et al. (2020)[29]	Plant terrestrialization and streptophyte algae genetics	Genomic studies of *Mesostigma viride* and *Chlorokybus atmophyticus* demonstrated key traits enabling the shift from aquatic to terrestrial life.
Liu et al. (2021)[30]	Angiosperms' NLR gene evolution	Found reduction of NLR genes linked to ecological specialization and streamlined immune systems, reflecting evolutionary trade-offs in angiosperms.
Alvarenga & Rousk (2022)[31]	Mosses and microbial symbioses	Showed mosses' bacterial symbiosis plays a major role in carbon and nitrogen cycles, especially in northern ecosystems, highlighting evolutionary importance.

Algal symbiosis is crucial for boosting the photosynthetic power of flowering plants (angiosperms). Algae provide extra pigments and a larger surface area for light absorption, which increases the conversion of solar energy into the sugar's plants need[32]. These specialized pigments absorb light wavelengths that plant chlorophyll misses, optimizing light use. This enables angiosperms to perform efficient photosynthesis even in shady or low-light conditions, effectively expanding their natural ecological range.

6. Soil Fertility and Nutrient Cycling

Algae are essential players in maintaining soil fertility and nutrient availability. For instance, cyanobacteria (a type of algae) fix atmospheric nitrogen, converting it into forms plants can use, thereby enhancing soil quality and supporting nearby vegetation. Furthermore, algae decompose organic matter, which releases vital nutrients back into the soil to nourish other plants. They also help mobilize critical mineral elements like potassium and phosphorus, ensuring long-term soil health and productivity[33].

7. Adaptation to Environmental Stress

Through symbiosis, algae significantly increase the resilience of angiosperms to various environmental stressors. In dry, arid environments, algae help plants optimize water usage and confer drought resistance. They also provide protection against salinity and low temperature stress[34]. Additionally, algae synthesize protective molecules, like antioxidants, that safeguard their host plants, allowing them to thrive even in challenging habitats.

8. Contribution to Ecosystem Biodiversity

Algal symbionts contribute to maintaining **ecosystem biodiversity** by supporting plant diversity and influencing community composition. By promoting host fitness, algae indirectly shape competitive interactions and the overall structure of plant communities. Additionally, algal symbioses create microhabitats and niches for other organisms such as bacteria, fungi, and invertebrates, fostering complex ecological networks and enhancing ecosystem richness.

Table 2: Key Studies on Algal Symbiosis, Sulphated Polysaccharides, and Plant Evolution

Authors	Subject	Result
Rehman et al. (2023)[35]	Cyanobacterial nitrogen fixation in angiosperms	Highlighted cell-to-cell symbiosis with genera like *Nostoc* and *Anabaena*, showing reduced CO_2 fixation but improved N_2 fixation, enhancing plant growth.
Lee & Ho (2022)[36]	Sulphated polysaccharides (SPs) in plants and algae	SPs such as carrageenan and agar protect marine algae from desiccation and salinity; review emphasized their evolutionary role in plant adaptation.
McCourt et al. (2023)[37]	Evolution of green plants to land	Reviewed mechanisms and adaptations that enabled transition from aquatic to terrestrial habitats, stressing nonlinear evolutionary pathways.
Lyu et al. (2023)[38]	Duckweed survival strategies	Showed adaptations such as adventitious organs, clonal variation, and rapid growth; highlighted cooperative strategies for survival across environments.

9. Impact on The Evolutionary Success of Angiosperms

The extraordinary evolutionary success of angiosperms (flowering plants) is largely due to their powerful symbiotic relationships with algae and cyanobacteria.

Enhanced Photosynthesis: By incorporating algal symbionts, angiosperms significantly boosted their photosynthetic capacity. This surge in energy production provided extra carbohydrates essential for metabolic processes and growth, which in turn enabled the rapid spread and dominance of flowering plants across the globe.

Nitrogen Fixation: Symbiosis with cyanobacteria offered a crucial lifeline: a steady supply of fixed nitrogen. This allowed angiosperms to flourish even in nutrient-poor environments, essentially opening up vast terrestrial landscapes for colonization.

Stress Tolerance: The partnerships with algae also conferred significant adaptive advantages. This biological buffer helped angiosperms withstand harsh environmental challenges, such as drought, extreme temperature fluctuations, and high salinity, making them incredibly resilient pioneers.

Conclusion

This review concludes that algal symbiosis profoundly shapes the ecological trajectory and adaptability of angiosperms. The associated benefits—notably enhanced nutrient acquisition, greater stress tolerance, and superior photosynthetic efficiency—are critical contributors to plant growth, resilience, and ecological competitiveness. Furthermore, at an evolutionary level, these symbiotic relationships furnished angiosperms with essential capabilities like nitrogen-fixing potential and tolerance for extreme environments, which significantly facilitated their global radiation and subsequent dominance. Therefore, algal symbiosis is demonstrably a paramount driver of the ecological stability and evolutionary prosperity of flowering plants, vital for both individual plant health and the broader dynamics of biodiversity and ecosystem resilience.

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Authors' Contribution

NG: Investigation, Data curation, Methodology, Writing-original draft; RSC: Conceptualization, Overall supervision, Writing-review & editing; DG: Resources and Data curation.

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