



The Green Engines of the Future: Unlocking the Power of Microalgae

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ABSTRACT

Microalgae comprise a diverse group of photosynthetic microorganisms with significant ecological and biotechnological importance. Their high photosynthetic efficiency, rapid growth, carbon dioxide fixation capacity, and ability to synthesize proteins, lipids, pigments, antioxidants, and other bioactive metabolites make them promising resources for sustainable bioprocessing. The principal stages involved in microalgal cultivation and biotechnological utilization, encompassing strain collection, isolation, culture establishment, media formulation, strain selection, cultivation optimization, strain improvement, scale-up, harvesting, and downstream processing. Particular emphasis is given to the effects of key physicochemical and operational parameters, including light intensity and photoperiod, temperature, salinity, pH, carbon availability, nutrient supply, and mixing, on growth and biomass productivity. The potential of strain improvement approaches to enhance biomass yield, metabolite accumulation, environmental stress tolerance, culture stability, and harvesting characteristics is also discussed. Furthermore, the transition from laboratory-scale cultures to pilot- and industrial-scale production is examined, with emphasis on the technical constraints associated with light attenuation, temperature variability, gas transfer, nutrient gradients, hydrodynamic stress, and biological contamination. The major applications of microalgal biomass and metabolites in aquaculture, food and nutraceutical production, pharmaceuticals, cosmetics, biofuels, wastewater treatment, bioremediation, and carbon capture are highlighted. The integration of appropriate strain selection, controlled cultivation, strain improvement, scalable production systems, and efficient downstream processing is essential for improving the productivity and economic feasibility of microalgal biotechnology and for supporting its contribution to a sustainable bio economy.

KEYWORDS

Microalgae; Microalgal cultivation; bioactive compounds; strain selection; aquaculture

Introduction

Microalgae are microscopic photosynthetic organisms that inhabit a wide range of aquatic environments, including marine, freshwater, and brackish water ecosystems. They are often called the green engines of the Future. They are among the oldest life forms on Earth and contribute nearly 50% of the global oxygen production through photosynthesis. As primary producers, microalgae form the foundation of aquatic food webs by converting solar energy into organic matter that supports higher trophic levels. Owing to their rapid growth rates, efficient carbon dioxide fixation, and ability to synthesize a diverse range of valuable biomolecules, microalgae have emerged as one of the most promising biological resources for sustainable biotechnology. They are widely used in aquaculture, biofuel production, pharmaceuticals, nutraceuticals, cosmetics, agriculture, wastewater treatment, and carbon sequestration. Despite their enormous potential, successful commercialization requires careful attention to every stage of the production process, from field collection and laboratory cultivation to strain improvement and large-scale cultivation. Based on their major taxonomic and phylogenetic affinities, commercially relevant microalgae include representatives of Chlorophyta (Green algae), Bacillariophyta (Diatoms), Dinoflagellata, Haptophyta, Ochrophyta other stramenopiles, Rhodophyta and Euglenophyta, among others. Green microalgae such as *Chlorella*, *Scenedesmus*, *Tetraselmis* and *Dunaliella* (Fig.1) are important sources of biomass, pigments, proteins and other bioactive compounds. Diatoms, including

Chaetoceros, *Thalassiosira*, *Skeletonema* and *Phaeodactylum*, are particularly important in aquaculture because of their favourable nutritional profiles and production of essential polyunsaturated fatty acids. Haptophytes such as *Tisochrysis* and *Pavlova* are also widely used as live feeds in hatchery production. In addition, *Nannochloropsis*, a member of the stramenopiles lineage, has considerable commercial importance because of its high lipid content and value as an aquaculture feed organism. Cyanobacteria, although prokaryotic and taxonomically distinct from true eukaryotic microalgae, are commonly included in discussions of commercial microalgal biotechnology; *Arthrospira* spp., commercially marketed as “Spirulina,” are a prominent example. Thus, the commercial microalgal sector encompasses a phylogenetically diverse collection of organisms whose value is determined not only by their taxonomy but also by their growth characteristics, biochemical composition and suitability for specific applications.

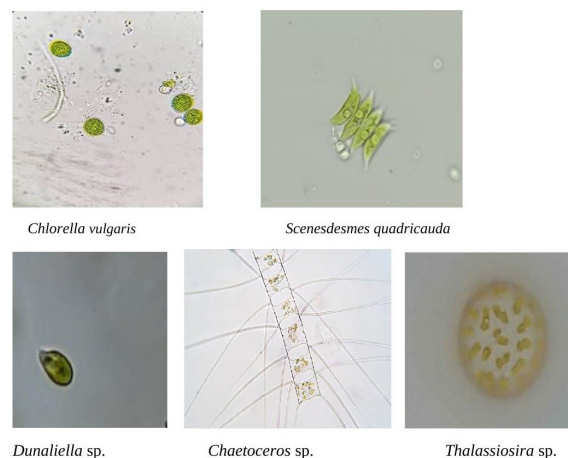


Figure 1. Microalgal Species used for Culture

Collection of Live Microalgae from Natural Environments

The collection of live microalgae from their natural habitats. The diversity of microalgae is immense, and different environments harbour species that possess unique physiological and biochemical characteristics. Marine coastal waters, estuaries, lagoons, mangrove ecosystems, freshwater lakes, reservoirs, rivers, aquaculture ponds, hypersaline environments, and even wastewater treatment facilities serve as valuable sources of microalgal biodiversity. Sampling is generally performed during periods of high biological productivity, when environmental conditions favour rapid algal growth.

Collection methods depend on the target species and habitat. Planktonic microalgae are commonly collected using plankton nets with mesh sizes ranging from 10 to 20 μm , while water samples can also be collected using Niskin bottles, Van Dorn samplers, or sterile sampling bottles. Benthic species are obtained by gently scraping rocks, sediments, submerged plants, or artificial substrates. During field sampling, researchers should record environmental variables such as water temperature, salinity, pH, dissolved oxygen, turbidity, nutrient concentrations, chlorophyll-a, and light intensity, as these parameters provide valuable information for recreating optimal laboratory culture conditions. To maintain cell viability, collected samples should be transported in clean, sterile, airtight containers under cool and shaded conditions. Excessive exposure to sunlight or high temperatures during

transportation should be avoided, as these conditions may reduce cell viability and alter the natural community composition (Fig.2).

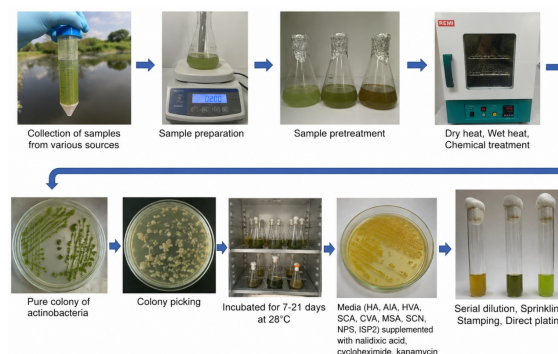


Figure 2. Sequential Steps in Microalgal Sampling, Isolation, and Pure Culture Development.

Laboratory Preparation for Microalgal Culture

A properly designed laboratory is essential for successful microalgal cultivation. Maintaining sterile conditions throughout the culture process minimizes contamination and ensures reproducible experimental results. Laboratory facilities should include a laminar airflow cabinet for aseptic manipulations, an autoclave for sterilization, incubators or controlled growth chambers, refrigerators for media storage, microscopes for routine observations, centrifuges, spectrophotometers, pH meters, conductivity meters, analytical balances, and air supply systems. All glassware, culture vessels, pipettes, and culture media should be sterilized before use. Glassware is usually sterilized by autoclaving at 121°C for 15–20 minutes under 15 psi pressure. Heat-sensitive solutions, including vitamins and certain antibiotics, are sterilized using membrane

filtration through 0.22 µm filters. The laboratory should maintain strict aseptic techniques, including disinfecting work surfaces, wearing gloves, and minimizing airborne contamination during inoculation. Proper environmental control is equally important. Culture rooms should maintain stable temperature, light intensity, and photoperiod while providing sufficient aeration and carbon dioxide to support photosynthesis and cell growth.

Culture Media and Chemicals Required for Microalgal Growth

Microalgae require a carefully balanced nutrient medium that supplies all essential elements needed for cellular growth and metabolism. These nutrients include macronutrients, micronutrients, trace metals, vitamins, and, for marine species, appropriate salt concentrations. Nitrogen is typically supplied as sodium nitrate, potassium nitrate, or ammonium salts, while phosphorus is provided as sodium or potassium phosphate. Diatoms additionally require dissolved silicate for frustule formation. Trace elements such as iron, manganese, zinc, copper, cobalt, and molybdenum function as enzyme cofactors involved in photosynthesis, respiration, and nutrient assimilation. Vitamins including thiamine (Vitamin B1), biotin (Vitamin B7), and cyanocobalamin (Vitamin B12) are required by many species for normal cellular metabolism. Several standardized culture media have been developed for different groups of microalgae. F/2 medium is widely used for marine phytoplankton, Conway medium is common in aquaculture hatcheries, Walne medium

supports mass production of live feeds, BG-11 is suitable for cyanobacteria, Bold's Basal Medium (BBM) is widely used for freshwater green algae, Chu-10 medium supports freshwater phytoplankton, and Zarrouk medium is specifically formulated for *Arthrospira* (*Spirulina*). The choice of medium depends on the nutritional requirements and intended application of the target species.

Isolation of Pure Microalgal Cultures

Natural water samples contain complex communities consisting of numerous algal species together with bacteria, fungi, protozoa, viruses, and small zooplankton. Therefore, obtaining pure cultures is essential before physiological, molecular, or biochemical studies can be performed. Isolation aims to separate a single algal species from mixed populations while minimizing contamination. Several isolation techniques are commonly employed depending on the characteristics of the target organism. Serial dilution reduces cell density until individual cells can be cultured separately. Micropipette isolation involves selecting a single cell or colony under an inverted microscope using a sterile glass micropipette (Fig.3). Agar plating techniques allow individual colonies to develop on solid nutrient media, facilitating isolation of pure strains. Flow cytometry and fluorescence-activated cell sorting (FACS) represent advanced approaches capable of rapidly isolating specific cells based on their fluorescence characteristics and size. Following isolation, cultures are repeatedly subculture under sterile conditions to

eliminate contaminating microorganisms. Regular microscopic examination and molecular verification help ensure that cultures remain axenic and genetically stable.

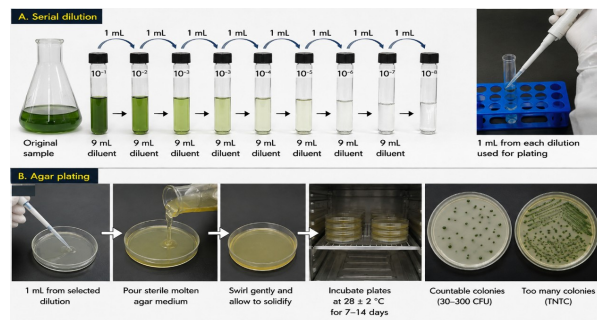


Figure 3. Isolation of Microalgae Using Serial Dilution and Agar Plating Techniques.

Environmental Factors Affecting Microalgal Growth

The growth and productivity of microalgae are strongly influenced by environmental conditions. Light is the primary energy source for photosynthesis, and both light intensity and photoperiod determine photosynthetic efficiency. Insufficient light limits growth, whereas excessive illumination may cause photo inhibition and oxidative stress. Temperature influences enzyme activity, membrane fluidity, and metabolic processes. Most commercially cultivated species grow optimally between 20°C and 30°C, although some polar or thermophilic species tolerate much broader temperature ranges.

Salinity regulates osmotic balance and varies considerably among freshwater, brackish, and marine species. Similarly, pH affects nutrient availability and enzyme function, with most species preferring values between 7.0 and 8.5. Carbon dioxide serves as

the primary carbon source for photosynthesis and is often supplied through aeration systems to enhance productivity. Proper mixing improves nutrient distribution, prevents sedimentation, facilitates gas exchange, and ensures that all cells receive adequate light exposure.

Selection of the Best Microalgal Strains

The selection of appropriate microalgal strains is one of the most critical decisions in any cultivation program. The ideal strain depends on the intended application, whether biomass production, lipid extraction, pigment synthesis, wastewater treatment, or aquaculture feed. An ideal commercial strain should exhibit rapid growth, high biomass productivity, efficient photosynthesis, elevated lipid or protein content, resistance to contamination, tolerance to environmental fluctuations, genetic stability, and ease of harvesting. Species capable of thriving under outdoor conditions with minimal nutrient requirements are generally preferred for industrial cultivation. Screening large numbers of naturally occurring isolates enables researchers to identify strains possessing superior physiological and biochemical characteristics.

Why Do We Need to Improve Microalgal Strains?

Microalgal strain improvement is essential to enhance the commercial viability and sustainability of large-scale microalgal cultivation. Although many naturally occurring microalgae possess valuable biochemical properties, wild strains often exhibit limitations such as slow growth, low

biomass yield, poor stress tolerance, and inconsistent metabolite production under industrial conditions. Improving microalgal strains helps achieve higher biomass productivity, enabling greater biomass production within shorter cultivation periods. It also promotes better product accumulation, increasing the yield of valuable compounds such as lipids, proteins, carbohydrates, pigments, antioxidants, and other bioactive metabolites. Enhanced strains are better adapted to high light intensities and fluctuating temperatures, allowing stable growth under outdoor cultivation conditions. Improved tolerance to high salinity, wastewater, and other environmental stresses enables the use of alternative water resources, reducing freshwater consumption and production costs. Strain improvement also enhances carbon dioxide utilization efficiency, resulting in increased photosynthetic performance, higher carbon sequestration, and improved biomass production. Furthermore, genetically stable strains exhibit greater culture stability, maintaining consistent productivity over extended cultivation periods. Increased resistance to contamination by competing microorganisms, bacteria, fungi, and grazers minimizes the risk of culture collapse and improves production reliability. Finally, improving cell characteristics that facilitate easier harvesting and dewatering reduces one of the most expensive steps in microalgal production, thereby lowering overall processing costs. Collectively, these improvements increase productivity, reduce operational costs, and support the successful commercialization of microalgae for applications in aquaculture, biofuels,

nutraceuticals, pharmaceuticals, wastewater treatment, and carbon capture.

Harvesting and Downstream Processing

Harvesting microalgal biomass represents one of the most energy-intensive and expensive stages of production. Since microalgae are extremely small and suspended in large volumes of water, efficient separation methods are required. Common harvesting techniques include centrifugation, membrane filtration, sedimentation, dissolved air flotation, and chemical or bio flocculation. After harvesting, biomass is washed, concentrated, and dried using spray drying, freeze drying, or solar drying depending on the intended application. Valuable compounds such as lipids, proteins, pigments, antioxidants, and bioactive molecules are subsequently extracted using physical, chemical, or enzymatic methods.

Technical Methods for Scaling Up Microalgal Cultivation

Successful industrial production requires gradual expansion from laboratory cultures to large-scale cultivation systems. Scale-up typically begins with agar plates and small flasks before progressing to larger culture vessels, carboys, bench-scale photobioreactors, pilot-scale reactors, and finally industrial production units. At each stage, inoculum quality must be maintained while minimizing contamination and physiological stress. Careful monitoring of cell density, nutrient concentrations, temperature, pH, dissolved oxygen, carbon dioxide supply, and light availability ensures healthy culture development throughout the scaling process.

Industrial cultivation may employ open raceway ponds or closed photo- bioreactors depending on species characteristics, production goals, environmental conditions, and economic considerations(Fig.4).

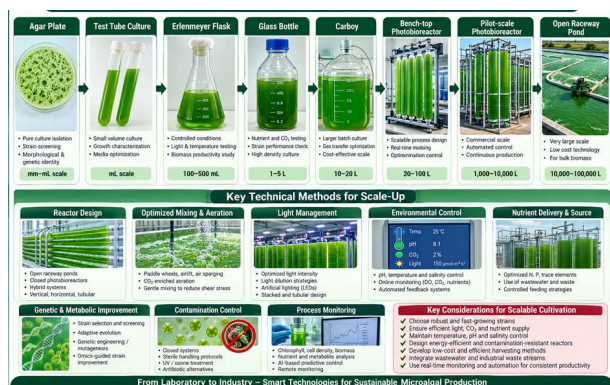


Figure. 4 Technical methods for scaling up microalgal cultivation

Why Do Promising Microalgae Perform Poorly at Industrial Scale?

Microalgal strains that exhibit excellent growth and productivity under controlled laboratory conditions often fail to perform similarly when cultivated at an industrial scale because scaling up does not eliminate biological weaknesses, it continuously exposes and amplifies them. In laboratory cultures, environmental conditions such as light, temperature, nutrient availability, and gas exchange are carefully controlled, whereas large-scale cultivation systems are subject to fluctuating environmental and operational conditions. As cultivation volume increases, light distribution becomes uneven due to self-shading, resulting in reduced photosynthetic efficiency. Temperature is no longer stable and varies with weather conditions, affecting cellular metabolism and growth. Gas transfer becomes a major

engineering challenge, with insufficient carbon dioxide delivery and oxygen accumulation limiting photosynthesis. Mixing, which is gentle in laboratory flasks, becomes more vigorous in large reactors, creating shear stress that can damage sensitive cells while still failing to distribute light and nutrients uniformly. Nutrient availability also becomes non-uniform because of concentration gradients and diffusion limitations, causing variations in growth and biomass composition. Furthermore, contamination is no longer an occasional risk but a continuous challenge, as industrial systems are constantly exposed to bacteria, fungi, protozoa, competing algae, and grazers that can rapidly reduce productivity or even cause complete culture collapse. Therefore, successful industrial-scale microalgal cultivation requires not only high-performing strains but also robust cultivation systems, efficient reactor design, precise environmental control, and effective contamination management to maintain consistent productivity.

Applications of Microalgae

Microalgae are emerging as versatile bioresources with applications across multiple sectors because of their ability to produce proteins, lipids, pigments, antioxidants and other high-value bioactive compounds. In aquaculture, they serve as essential live feeds for fish, shrimp, molluscs and zooplankton. In the food and nutraceutical industries, microalgal biomass provides proteins, vitamins, omega-3 fatty acids and natural pigments. Their bioactive metabolites are also being explored for pharmaceutical and

cosmetic applications, including antioxidant, antimicrobial, anti-inflammatory and skin-care products. Environmentally, microalgae contribute to wastewater treatment, nutrient recovery, carbon capture and bioremediation (Fig.5). They are also being investigated as renewable feedstocks for biofuels and other bioproducts, positioning microalgae as important contributors to the emerging circular and low-carbon bioeconomy.



Figure 5. Diverse Applications of Microalgae across Industrial and Environmental Sectors.

Conclusion

Microalgae are emerging as powerful biological resources for a sustainable and

low-carbon bioeconomy, with applications spanning aquaculture, food, nutraceuticals, biofuels and environmental management. Unlocking their full commercial potential requires a complete pipeline from strain discovery and selection to cultivation, strain improvement, scale-up and efficient downstream processing. Despite challenges such as contamination, environmental fluctuations and high harvesting costs, advances in biotechnology and bioprocess engineering are accelerating their industrial development. The future of microalgal biotechnology lies in robust strains, efficient production systems and high-value bioproducts, transforming microscopic organisms into major drivers of sustainable innovation.

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