

Diatoms: A Nutritional Potential for Sustainable Applications: From Biochemical Composition to Bioeconomy and Climate Resilience

Simoni Singhal¹, Hirak Parikh², Archana Tiwari³ and Jyoti Verma^{1,*}

¹ Aquatic Ecology, Department of Zoology, CMP Degree College, University of Allahabad, Prayagraj 211002, Uttar Pradesh, India

² Department of Earth and Environmental Systems, Indiana State University, Terre Haute, IN 47809, USA

³ Amity Institute of Biotechnology, Amity University, Noida 201303, Uttar Pradesh, India

* Correspondence: jyoti.zoo@cmpcollege.ac.in

How To Cite: Singhal, S.; Parikh, H.; Tiwari, A.; et al. Diatoms: A Nutritional Potential for Sustainable Applications: From Biochemical Composition to Bioeconomy and Climate Resilience. *Algae and Environment* **2026**, 2(1), 3. <https://doi.org/10.53941/algaeenviron.2026.100003>

Received: 20 July 2026

Revised: 4 September 2026

Accepted: 23 October 2026

Published: 28 October 2026

Abstract: Diatoms are ecologically important microalgae with considerable potential for sustainable applications owing to their diverse biochemical composition and environmental adaptability. This review examines their nutritional composition, including proteins, lipids, carbohydrates, omega-3 polyunsaturated fatty acids, pigments and other bioactive compounds, and evaluates their applications in aquaculture, nutraceuticals, functional foods and emerging biotechnological systems. Particular attention is given to species-specific variation in biochemical composition and the influence of cultivation conditions, nutrient availability, light, temperature and growth phase on biomass productivity and metabolite accumulation. Protein abundance is considered separately from nutritional quality, while fatty acid profiles are discussed in relation to the quantitative evidence available for individual taxa. The review further explores diatom-based biorefinery approaches and their contribution to a circular bioeconomy through the recovery of multiple value-added products from biomass. Climate resilience is addressed by examining how environmental change and cultivation stressors may alter diatom growth, biochemical composition and the reliability of biomass production. Despite their potential, broader application remains constrained by strain-dependent variability, incomplete nutritional characterization, analytical inconsistencies, downstream processing costs and challenges in scaling cultivation systems. Standardization of analytical methods, systematic strain selection, improved cultivation strategies and scalable production systems are therefore essential for reliable product characterization and commercial translation. Integrating nutritional evidence with environmental sustainability and techno-economic considerations may strengthen the role of diatoms in sustainable food and feed systems and the emerging bioeconomy.

Keywords: nutritional profiling; freshwater ecosystem; biochemical composition; diatom; silica frustule

1. Introduction

Diatoms (Bacillariophyta) represent one of the most ecologically consequential and metabolically distinctive lineages of photosynthetic eukaryotes. They occur across marine, freshwater, brackish, benthic, pelagic, ice-associated, and other environmentally heterogeneous habitats, where their distributions are shaped by gradients in



Copyright: © 2026 by the authors. This is an open access article under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Publisher's Note: Scilight stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

light, temperature, salinity, nutrient availability, hydrodynamics, and dissolved inorganic carbon. Their ecological significance is therefore not adequately captured by the conventional representation of diatoms as predominantly planktonic bloom-forming organisms. In addition to their contribution to pelagic primary production, benthic diatoms can form dense microphytobenthic communities and contribute substantially to sedimentary carbon fixation and nutrient cycling, particularly in shallow aquatic systems. Estimates of their contribution to global primary production vary according to the spatial and methodological framework employed, but diatoms are consistently recognized as major contributors to marine and global carbon fixation, with commonly cited estimates of approximately one-fifth of global primary production [1–3].

A defining characteristic of diatoms is their silicified cell wall, or frustule, which is structurally and functionally integrated with cellular metabolism. Biosilica formation is not simply a morphological feature; it is coupled to nutrient acquisition, polyamine metabolism, cellular architecture, and the cycling of silicon in aquatic ecosystems. At the same time, diatoms possess an evolutionary history that distinguishes their metabolism from that of green microalgae and terrestrial plants. Their plastids originated through secondary endosymbiosis involving a red-algal lineage, resulting in complex plastids and a mosaic cellular metabolism shaped by genes and biochemical pathways of diverse evolutionary origins [4,5]. This evolutionary complexity is reflected in the compartmentalization and integration of carbon, nitrogen, lipid, pigment, and silicon metabolism.

The metabolic organization of diatoms provides an important basis for understanding their nutritional potential. Unlike a simple accumulation of commercially valuable compounds, diatom biomass represents the outcome of dynamic allocation of cellular carbon and nitrogen among structural, storage, membrane, and secondary metabolites. The ornithine–urea cycle, for example, is an important metabolic feature of diatoms that links carbon and nitrogen redistribution and contributes to the cellular response to changing nitrogen availability. Its integration with nitrogen assimilation, the tricarboxylic acid cycle, amino-acid metabolism, and pathways associated with silica formation illustrates why nutrient availability cannot be considered independently from diatom biochemical composition [6].

This metabolic plasticity underpins the diversity of compounds detected in diatom biomass, including proteins and amino acids, storage and membrane lipids, long-chain polyunsaturated fatty acids (PUFAs), pigments, carbohydrates, sterols, vitamins, minerals, and structurally associated biomolecules. Among these, eicosapentaenoic acid (EPA), fucoxanthin, chrysolaminarin, and protein-rich biomass have received considerable attention because of their potential applications in aquaculture, food and feed systems, nutraceuticals, cosmetics, pharmaceuticals, and biorefinery platforms. Diatoms are also capable of trophic flexibility, with some species able to use organic carbon under mixotrophic or heterotrophic conditions, potentially modifying biomass productivity and the accumulation of target metabolites [7,8].

However, the nutritional value of a diatom should not be interpreted from total biochemical concentration alone. Protein content, for example, does not necessarily indicate protein quality without considering amino-acid composition, digestibility, bioavailability, and the nutritional requirements of the intended consumer. Similarly, a high total lipid concentration does not necessarily correspond to high EPA productivity, because nutrient stress can increase storage triacylglycerols while simultaneously reducing growth and altering membrane lipid composition. EPA responses may consequently differ among species, strains, growth phases, and stress intensities. The same principle applies to pigments such as fucoxanthin, whose abundance can change in response to light and nutrient conditions in a species- and stress-dependent manner. Thus, concentration, composition, and productivity represent distinct nutritional attributes and should not be treated as interchangeable measures of biotechnological performance.

Species and habitat diversity further complicate attempts to define a universal “diatom nutritional profile.” Frequently investigated taxa such as *Phaeodactylum tricornutum*, *Thalassiosira pseudonana*, *Skeletonema costatum*, *Chaetoceros* spp., and *Odontella aurita* have generated a substantial proportion of the experimental evidence underlying current perceptions of diatom biotechnology. Nevertheless, these model systems represent only a fraction of diatom ecological and physiological diversity. Freshwater and benthic taxa, including pennate diatoms adapted to highly variable irradiance, desiccation, nutrient limitation, sediment-associated conditions, and other environmental stresses, remain comparatively less represented in nutritional and industrial studies. Reviews of diatom ecosystem services likewise demonstrate that diatoms occur across both pelagic and benthic production systems, reinforcing the need to move beyond a predominantly marine-planktonic evidence base.

This taxonomic imbalance is particularly important because environmental adaptation can influence biochemical allocation. Diatoms inhabiting nutrient-poor waters, sediments, polar environments, hypersaline habitats, or fluctuating light regimes may possess physiological traits that differ substantially from those of laboratory-maintained planktonic strains. Consequently, nutritional composition reported for one strain under a defined cultivation regime cannot automatically be generalized to the species, genus, habitat, or diatoms as a whole. Differences in culture medium, salinity, temperature, irradiance, nutrient regime, carbon source, growth phase,

cultivation mode, and analytical methodology can all contribute to variation among reported values. Recent work on trophic flexibility similarly emphasizes that growth mode can alter both biomass formation and biochemical productivity, further demonstrating that nutritional traits are context-dependent rather than fixed species characteristics [9–11].

An additional challenge arises from the analytical characteristics of diatom biomass itself. The biosilica frustule provides structural rigidity that can influence cell disruption, extraction efficiency, and the recovery of intracellular compounds. Consequently, reported differences in protein, lipid, pigment, or carbohydrate concentrations may reflect not only biological variation but also differences in biomass preparation, cell-disruption efficiency, extraction chemistry, analytical platforms, and conversion factors. Comparisons based solely on numerical ranges are therefore potentially misleading unless experimental and analytical conditions are reported alongside the biochemical measurements. A robust nutritional assessment requires separation of dry-weight concentration, volumetric concentration, biomass productivity, and target-metabolite productivity, together with adequate documentation of cultivation and analytical conditions.

These limitations expose an important distinction between demonstrating the presence of nutritionally valuable molecules and establishing their translational potential. Evidence for a compound's biochemical occurrence does not necessarily establish its nutritional quality, physiological efficacy, safety, scalability, economic feasibility, or regulatory acceptability. This distinction is especially relevant for diatom-derived products intended for human food, animal feed, and nutraceutical applications, where contaminants, trace-element accumulation, digestibility of frustule-associated material, residual processing chemicals, and cultivation-source effects require explicit evaluation. Biomass generated through wastewater-associated cultivation, for example, cannot automatically be considered equivalent to food- or feed-grade biomass because the cultivation matrix may introduce contaminants that require independent safety assessment.

Accordingly, the concept of diatoms as nutritional resources requires a shift from species-level descriptions and isolated metabolite measurements toward an integrated, evidence-weighted assessment of taxonomic identity, ecological origin, cultivation conditions, biochemical composition, analytical methodology, productivity, bioavailability, safety, and end-use suitability. Such an approach is particularly important for developing diatom-based biorefineries, where maximizing one metabolite may compromise biomass productivity, another nutritional component, or downstream processing efficiency. The objective should therefore not be to identify a universally superior diatom, but to determine which taxa and cultivation strategies are appropriate for specific nutritional or biotechnological targets [12,13].

Against this background, this review critically examines the nutritional potential of diatoms through a comparative and mechanistic framework. First, it considers the ecological and evolutionary diversity underlying diatom metabolic specialization. It then evaluates the biochemical basis and variability of proteins, amino acids, lipids and PUFAs, carbohydrates and functional polysaccharides, pigments, minerals, and biosilica. Particular emphasis is placed on distinguishing biochemical concentration from productivity and on identifying the environmental and physiological variables responsible for observed differences among studies. The review subsequently examines analytical and cell-disruption constraints, evaluates the strength of evidence supporting proposed functional applications, and considers cultivation, biorefinery integration, food and feed safety, environmental applications, and climate-related claims. Finally, it identifies methodological, taxonomic, regulatory, and translational gaps that must be addressed before diatom nutritional resources can be reliably advanced from laboratory-scale characterization toward standardized and commercially relevant applications.

1.1. Research Directions in Diatom Nutritional Optimization

Recent research on diatom nutritional optimization has increasingly shifted from descriptive biochemical characterization toward mechanistic investigation of metabolic plasticity. Advances in transcriptomics, proteomics, metabolomics, and lipidomics have enabled researchers to associate changes in environmental conditions with alterations in carbon partitioning, nitrogen assimilation, lipid remodeling, pigment metabolism, and stress responses. Rather than functioning as independent analytical approaches, these technologies increasingly provide complementary information on how cellular metabolism is reorganized when diatoms encounter nutrient limitation, changes in irradiance, temperature fluctuations, or other environmental constraints [14]. The key research gaps and technological barriers limiting the advancement of diatom biotechnology are summarized in Figure 1, highlighting the need for improved strain characterization, optimized cultivation strategies, efficient biomass harvesting, and scalable, economically viable production systems.

Nutrient availability remains one of the principal determinants of diatom biomass composition, but its effects are strongly dependent on species, strain, physiological state, and stress intensity. Nitrogen limitation commonly

reduces protein synthesis and cellular growth while promoting redistribution of fixed carbon toward storage compounds, particularly triacylglycerols (TAGs), in many diatom species. However, increased total lipid or TAG content should not be interpreted automatically as enhanced production of nutritionally desirable polyunsaturated fatty acids. Nitrogen stress can simultaneously reduce biomass productivity and modify membrane lipid composition, such that responses of eicosapentaenoic acid (EPA) may differ in terms of its percentage of total fatty acids, cellular concentration, and volumetric productivity. Consequently, nutritional optimization requires simultaneous consideration of biomass yield, metabolite concentration, and target-compound productivity rather than maximizing a single biochemical parameter.

Research Gaps Hinder Diatom Commercialization

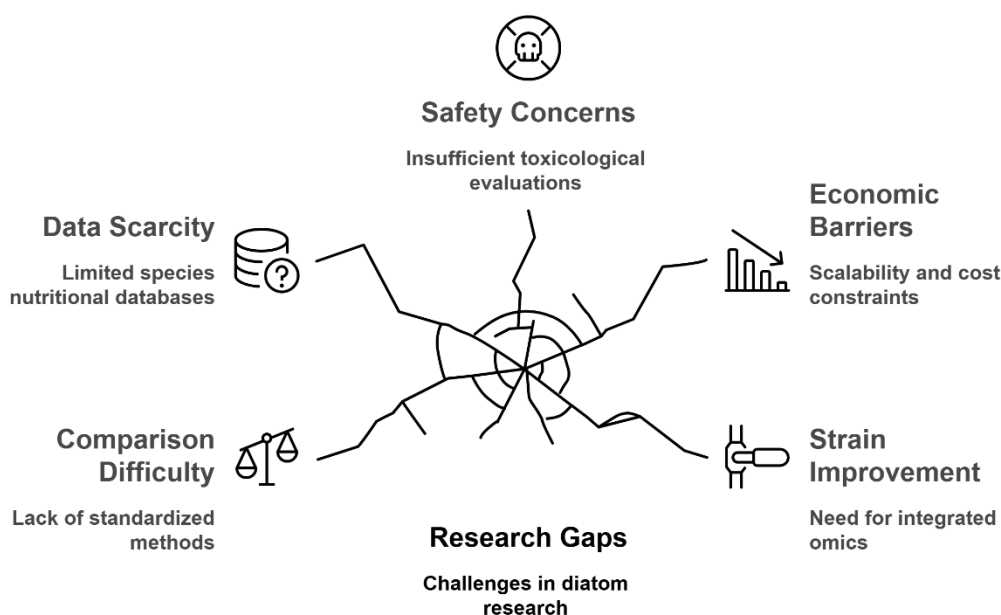


Figure 1. Major research gaps and constraints affecting the advancement of diatom biotechnology.

Phosphorus and silicon exert additional controls over cellular allocation. Phosphorus availability affects membrane lipid metabolism and energy transfer, whereas silicon availability is closely associated with frustule formation and cell-cycle progression in silicifying diatoms. Manipulation of these nutrients can therefore alter biochemical composition indirectly through effects on growth, cellular architecture, and metabolic demand. Experimental studies of *Chaetoceros*, *Thalassiosira*, *Phaeodactylum*, and *Skeletonema* have demonstrated that nutrient regimes can substantially modify biomass composition; however, the magnitude and direction of these responses are not sufficiently consistent to support universal cultivation rules [15–17].

Environmental stressors provide a second major route for metabolic optimization. Irradiance, temperature, photoperiod, salinity, pH, and light quality influence photosynthetic electron transport, oxidative balance, pigment composition, fatty-acid desaturation, and carbon allocation [18]. Importantly, these responses are frequently non-linear. Moderate stress may stimulate accumulation of particular protective or storage metabolites, whereas severe stress can suppress photosynthesis and reduce both biomass formation and target-product productivity. Pigment responses should therefore be interpreted in terms of photoprotective regulation and pigment stoichiometry rather than assuming that increasing stress invariably increases fucoxanthin accumulation. Species-specific responses, fucoxanthin-to-chlorophyll ratios, and interactions with other photoprotective pigments provide a more informative basis for evaluating pigment optimization.

The increasing availability of multi-omics datasets has also improved the resolution with which metabolic regulation can be investigated. Transcriptomic and proteomic analyses can identify candidate enzymes and regulatory nodes, while metabolomics and lipidomics provide complementary information on pathway outputs. Their greatest value lies in connecting molecular regulation with measurable changes in biomass composition and productivity. In this context, metabolic engineering offers opportunities to modify specific biosynthetic pathways; however, pathway manipulation must be evaluated against potential trade-offs among growth, cellular fitness, product stability, and downstream processing requirements. Evidence for successful pathway engineering therefore needs to be distinguished from predictions based solely on genomic or computational analyses.

Computational modelling and machine-learning approaches are emerging as complementary tools for integrating high-dimensional cultivation and omics datasets. Their potential lies primarily in identifying relationships among cultivation variables and predicting biomass or metabolite responses under defined experimental conditions. However, predictive models are only as reliable as the quality, taxonomic breadth, and experimental comparability of the datasets used for model development. At present, the limited representation of freshwater, benthic, and non-model diatoms, together with substantial variation in cultivation and analytical protocols, constrains the generalizability of such models. The major research approaches used to investigate and optimize nutritional composition and metabolic traits in diatoms are integrated into a conceptual framework (Figure 2), encompassing biochemical characterization, physiological assessment, cultivation optimization, and metabolic regulation.

Overall, recent progress indicates a transition from simply measuring biochemical composition toward understanding and controlling the physiological processes responsible for metabolite allocation. Nevertheless, nutritional optimization should not be framed as maximizing individual compounds in isolation. A more meaningful objective is to identify cultivation conditions that achieve an application-specific balance among biomass productivity, nutritional composition, target-metabolite yield, resource consumption, and product safety. This distinction is particularly important when comparing diatom taxa originating from different ecological and physiological backgrounds and provides the basis for the comparative nutritional and analytical framework developed in subsequent sections.

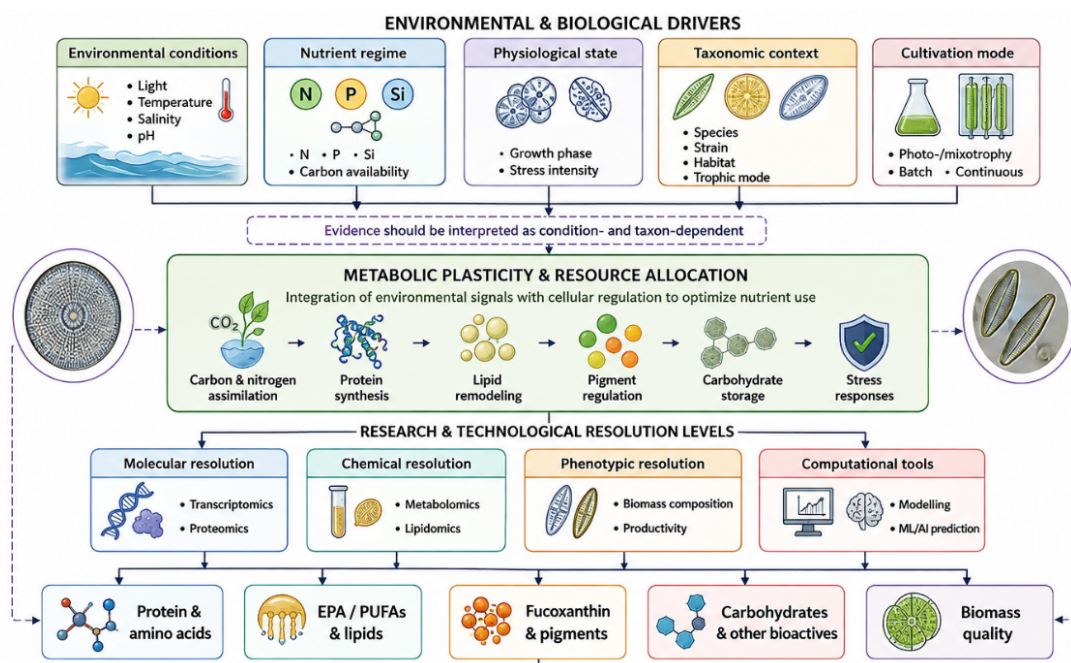


Figure 2. Conceptual framework illustrating the major research approaches used to investigate and optimize nutritional and metabolic traits in diatoms (Source: Authors' conceptual synthesis based on literature reviewed in this study).

1.2. Evolution of Research on Nutritional Profiling of Diatoms

Research on the nutritional characteristics of diatoms has progressively expanded from basic biochemical characterization toward increasingly integrated analyses of metabolic regulation and application-specific productivity (Figure 3). Early investigations primarily focused on determining the proximate composition of diatom biomass, including protein, lipid, carbohydrate, ash, and fatty-acid fractions. These studies established that diatoms can contain nutritionally relevant quantities of proteins, polyunsaturated fatty acids, pigments, and carbohydrates, but also demonstrated substantial variation among taxa and cultivation conditions. The subsequent development of chromatographic and spectrometric techniques enabled more detailed characterization of individual biochemical constituents. Fatty-acid profiling, pigment analysis, amino-acid characterization, and antioxidant assays expanded the nutritional assessment beyond bulk proximate composition. This analytical transition was important because total lipid or protein content alone provides limited information about the functional or nutritional value of biomass. For example, identification of specific PUFAs, carotenoids, amino acids,

or structurally distinct polysaccharides allows nutritional traits to be linked more directly with potential applications [19].

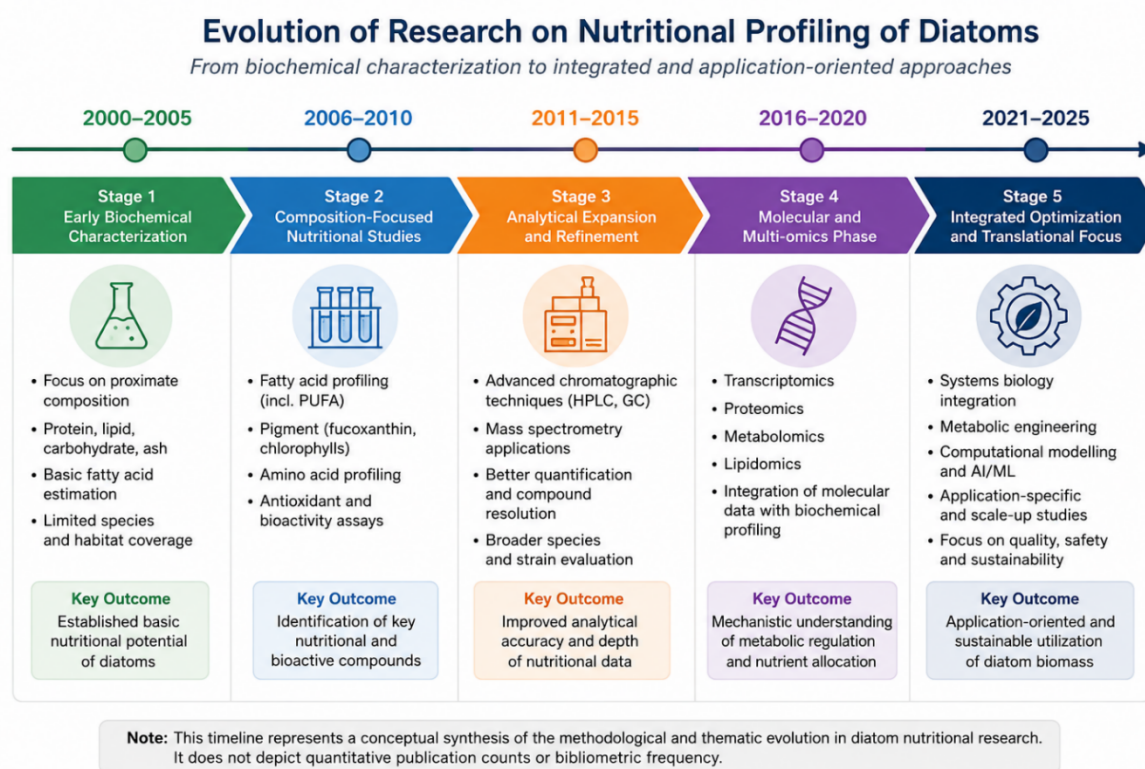


Figure 3. Timeline graph depicting the growth of research on nutritional profiling of diatoms (Source: Authors' conceptual synthesis based on literature reviewed in this study).

More recently, high-throughput molecular approaches have shifted attention from metabolite measurement toward the mechanisms regulating biochemical allocation. Transcriptomics, proteomics, metabolomics, and lipidomics have been increasingly used to investigate how nutrient availability and environmental stress modify metabolic pathways associated with lipid remodeling, nitrogen assimilation, pigment metabolism, carbon storage, and stress adaptation. These approaches have also strengthened the mechanistic interpretation of physiological responses by allowing changes in gene expression and protein abundance to be examined alongside changes in metabolite profiles. The current research landscape is therefore characterized by increasing integration among ecological context, cultivation conditions, molecular regulation, biochemical composition, and productivity. Metabolic engineering and computational modelling are being explored as additional tools for manipulating or predicting target-product formation. However, the evidence base remains unevenly distributed among taxa and habitats, with a strong representation of a relatively small number of marine model diatoms compared with freshwater, benthic, epiphytic, and environmentally extreme taxa. This taxonomic imbalance limits the extent to which findings from intensively studied laboratory strains can be generalized across diatom diversity.

An important development in this field is consequently the movement toward condition-resolved and application-specific nutritional assessment. Rather than treating nutritional composition as a fixed characteristic of a species, contemporary studies increasingly recognize that biomass quality emerges from interactions among genotype, habitat, cultivation conditions, physiological state, analytical methodology, and the biochemical endpoint being measured. This perspective also requires clearer separation of concentration from productivity and of total biochemical pools from nutritionally relevant molecular fractions.

Accordingly, the development of diatom nutritional research can be viewed not simply as an increase in publication volume, but as a transition in research emphasis: from proximate composition, through compound-specific characterization, toward mechanistic and multi-omics investigation, and ultimately toward integrated optimization and translational assessment. This qualitative progression provides a more defensible representation of research development than an unsupported publication-growth curve and establishes the context for evaluating the biochemical composition and nutritional potential of diatoms in the following sections.

1.3. Literature Search and Selection Methodology

A structured literature search and thematic narrative synthesis were undertaken to review the nutritional composition, biochemical properties, cultivation physiology, analytical characterization, and sustainable biotechnological applications of diatoms. Literature searches were conducted using Google Scholar, PubMed, and Scopus to identify relevant research articles and review papers. Publications from the preceding decade (2016–2026) were prioritized to capture recent advances, while earlier publications were included selectively when required to explain foundational concepts, established mechanisms, or standard analytical and cultivation methods.

The search strategy combined keywords relating to diatom biology and taxonomy with terms addressing biochemical composition, nutritional properties, environmental regulation, and biotechnological applications. Core search terms included diatoms, nutritional composition, protein, amino acids, lipids, polyunsaturated fatty acids, eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), carbohydrates, polysaccharides, fucoxanthin, pigments, and bioactive compounds. Additional terms included cultivation conditions, nutrient limitation, nitrogen, phosphorus, silicon metabolism, temperature, light intensity, growth phase, protein quantification, biomass productivity, photobioreactor, scale-up, harvesting, biorefinery, aquaculture, nutraceuticals, artificial intelligence, machine learning, bioeconomy, carbon utilization, and climate resilience. These terms were combined using Boolean operators and adapted to the search functions of the respective databases to retrieve literature relevant to the principal themes of the review.

The selection process involved an initial screening of titles and abstracts, followed by full-text assessment of publications considered potentially relevant to the review objectives. Studies were selected according to their thematic relevance, scientific contribution, and the availability of evidence supporting the findings or claims discussed. Primary research articles were prioritized for quantitative data on biochemical composition, fatty-acid profiles, metabolite productivity, cultivation performance, and physiological responses. Review articles were used to contextualize established knowledge, identify emerging research directions, and locate relevant primary studies. Earlier foundational publications were retained selectively where they provided essential methodological or conceptual information. Studies involving non-diatom microalgae were considered only for explicitly identified comparative purposes and were not treated as direct evidence of diatom-specific characteristics.

For quantitative data extraction and interpretation, reported values were examined in relation to species or strain identity, cultivation conditions, physiological state, analytical methods, and measurement units, wherever these details were available. Nutritional composition and productivity indicators were treated as distinct parameters, and values obtained under different experimental conditions were not assumed to be directly comparable. Mechanistic, physiological, and application-related claims were evaluated in relation to the scope of the supporting evidence. Particular care was taken to distinguish laboratory-scale findings from pilot-scale or commercial evidence, *in vitro* biological activity from demonstrated health effects, and potential carbon-utilization benefits from verified long-term carbon removal or sequestration.

The selected literature was synthesized thematically to evaluate diatom biochemistry and nutritional relevance, environmental regulation of metabolite production, analytical standardization, cultivation and production systems, emerging biotechnological applications, bioeconomy opportunities, and climate-related implications. This approach enabled the integration of recent experimental findings with established knowledge while identifying evidence limitations, methodological inconsistencies, and research gaps relevant to the sustainable utilization of diatoms.

2. Biochemical Composition and Nutritional Potential of Diatoms

The nutritional potential of diatoms arises from the simultaneous occurrence of proteins, amino acids, lipids, polyunsaturated fatty acids (PUFAs), carbohydrates, pigments, minerals, and structurally associated biomolecules. However, these constituents are not present at fixed proportions across diatom taxa. Their abundance and biochemical form are influenced by species and strain identity, ecological origin, growth phase, nutrient availability, irradiance, temperature, salinity, cultivation mode, and analytical methodology. The biochemical composition and nutritional potential of diatoms vary across taxa and cultivation conditions, reflecting differences in protein, lipid, carbohydrate, fatty-acid, and pigment profiles. These condition-dependent variations are illustrated for selected diatom taxa in Figure 4. Consequently, nutritional assessment should distinguish between biochemical concentration, molecular composition, biomass productivity, and target-compound productivity, rather than ranking taxa solely according to the abundance of a single constituent.

2.1. Proteins and Amino Acids

Diatoms can contain appreciable amounts of protein, but protein content alone is insufficient to establish nutritional quality. A more complete assessment requires information on amino acid composition, the availability of essential amino acids, digestibility and bioavailability. Accordingly, reported protein concentrations should be interpreted as indicators of biochemical composition rather than direct evidence of superior nutritional quality. Nevertheless, total protein concentration alone provides an incomplete assessment of nutritional quality because the biological value of a protein depends on its amino-acid composition, digestibility, bioavailability, and the requirements of the intended consumer [20].

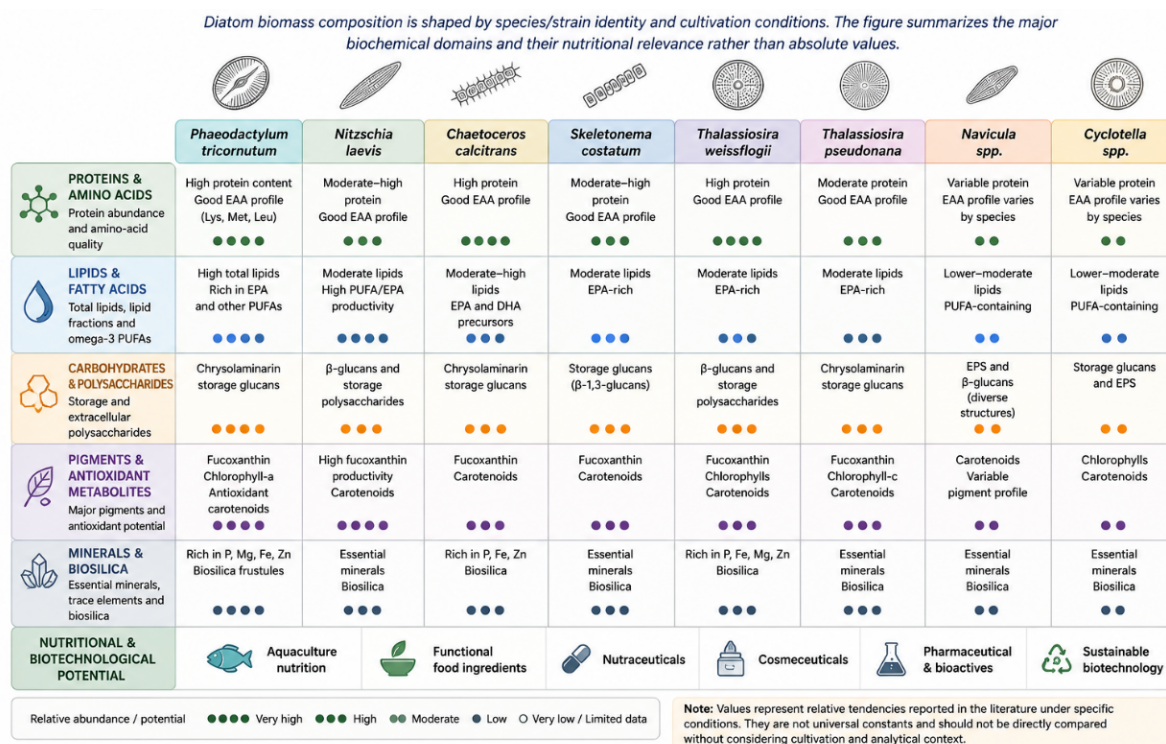


Figure 4. Condition-resolved biochemical architecture and nutritional potential of selected diatom taxa.

Comparative studies demonstrate substantial interspecific variation in protein accumulation among microalgae. *Phaeodactylum tricornutum* has been reported to contain approximately 43.29% protein under specific cultivation conditions, while other investigated microalgae exhibited different protein levels [14]. Protein contents of approximately 37.8% have also been reported for *P. tricornutum* biomass produced under pilot-scale cultivation conditions [21]. These findings suggest that substantial protein accumulation can be achieved beyond laboratory-scale cultivation. However, comparisons across studies should account for differences in growth media, cultivation systems, growth phase, analytical methods and reporting basis. Moreover, protein content alone does not establish nutritional quality, which also depends on amino acid composition, digestibility and bioavailability.

The amino-acid composition of diatom biomass is equally important. Several diatom species contain essential amino acids such as lysine, methionine, leucine, isoleucine, and threonine [7,20]. However, the nutritional adequacy of these amino acids should be evaluated relative to the requirements of the target organism rather than described generically as a “balanced” amino-acid profile. In feed applications, particular attention is required for potentially limiting amino acids such as lysine and sulfur-containing amino acids, especially when diatom biomass is incorporated into formulations dominated by plant-derived ingredients. Future nutritional evaluation should therefore report essential amino-acid scores, amino-acid digestibility, and, where possible, protein quality indices rather than relying exclusively on crude-protein percentage. Protein accessibility may also be influenced by the physical characteristics of diatom biomass. The silicified frustule and associated cellular structures can affect biomass disruption, extraction efficiency, and accessibility of intracellular macromolecules. Thus, reported protein concentrations may partly reflect differences in sample preparation and analytical recovery. For nutritional applications, the distinction between measured protein content and nutritionally accessible protein should consequently be maintained.

Overall, diatoms represent promising protein-rich biomass resources, but their suitability as alternative proteins depends on more than high crude-protein content. Species selection should incorporate amino-acid composition, digestibility, biomass productivity, cultivation requirements, downstream processing, and safety characteristics.

2.2. Lipids and Essential Fatty Acids

Lipids represent one of the most extensively investigated nutritional fractions of diatoms because many species synthesize long-chain PUFAs, particularly eicosapentaenoic acid (EPA; 20:5n – 3). EPA is an important nutritional lipid associated with cardiovascular, immune, inflammatory, and developmental functions and is consequently of interest for aquaculture, food, and nutraceutical applications [11]. Diatoms therefore represent potential alternatives or complementary sources to conventional marine-derived omega-3 resources.

The lipid phenotype of diatoms, however, cannot be adequately described using total lipid content alone. Total cellular lipids comprise structurally and functionally distinct fractions, including membrane phospholipids, glycolipids, neutral storage lipids, and triacylglycerols (TAGs). An increase in total lipid concentration may therefore result primarily from storage-lipid accumulation without a corresponding increase in nutritionally desirable EPA. For this reason, total lipid content, TAG accumulation, EPA proportion of total fatty acids, absolute EPA concentration, and EPA volumetric productivity should be reported as separate endpoints.

Comparative studies illustrate this distinction. Investigations involving *P. tricornutum*, *Skeletonema costatum*, *Chaetoceros calcitrans*, *Nitzschia laevis*, and other microalgae have demonstrated substantial differences in both lipid composition and productivity [7,12,15]. For example, *N. laevis* has been reported to achieve high PUFA productivity under particular cultivation conditions, whereas pilot-scale *P. tricornutum* biomass has exhibited substantial total lipid content [22]. Such observations indicate that the optimal taxon depends on whether the objective is maximizing biomass, total lipid, a specific PUFA, or volumetric production of the target molecule.

Nutrient stress can further alter lipid allocation. Nitrogen limitation frequently suppresses protein synthesis and growth while increasing the relative contribution of neutral storage lipids in many diatoms. Silicate limitation and changes in irradiance can also modify lipid metabolism and membrane composition [19]. Nevertheless, stress-induced lipid accumulation should not automatically be interpreted as improved nutritional quality. Severe nutrient limitation may decrease biomass productivity, alter membrane lipid homeostasis, and change the relative abundance of EPA and other PUFAs. The response is therefore dependent on species, strain, stress intensity, duration, growth phase, and the endpoint used for evaluation. An application-oriented assessment should consequently distinguish between lipid accumulation as a physiological stress response and sustainable production of nutritionally valuable lipids. The most relevant cultivation strategy is not necessarily the condition producing the highest lipid percentage, but the condition that provides an appropriate combination of biomass yield, EPA content, EPA productivity, stability, and downstream recovery.

2.3. Carbohydrates and Functional Polysaccharides

Diatom carbohydrates comprise chemically and functionally heterogeneous compounds rather than a single nutritional fraction. Important carbohydrate pools include intracellular storage glucans, extracellular polymeric substances (EPS), structural carbohydrates, and other soluble or cell-associated polysaccharides. Among these, chrysolaminarin is a major storage carbohydrate in many diatoms and is generally described as a β -glucan containing predominantly β -(1 $\rightarrow$ 3) linkages with β -(1 $\rightarrow$ 6) branches [23].

The biological and nutritional properties of diatom polysaccharides depend strongly on molecular structure. Molecular weight, degree and pattern of branching, monosaccharide composition, linkage type, sulfation, conformation, and purification procedure can influence their physicochemical and biological activities. Consequently, the term “ β -glucan” should not be treated as synonymous with a uniform bioactive compound. Reports of immunomodulatory, antioxidant, antimicrobial, or prebiotic effects [16,22] should instead be interpreted according to the chemical identity and experimental preparation of the polysaccharide investigated.

Diatom-derived EPS constitute another distinct carbohydrate pool. These polymers are released or associated with the cell surface and contribute to adhesion, biofilm development, aggregation, extracellular protection, and interactions with surrounding organisms. Their ecological functions differ from those of intracellular storage glucans, although both can contribute to the overall carbohydrate fraction of biomass.

Environmental conditions influence carbohydrate allocation through changes in cellular carbon balance. Nutrient limitation, particularly when nitrogen availability constrains protein synthesis, can promote redistribution of assimilated carbon toward storage compounds in some species [18]. However, the magnitude and direction of

this response are highly context dependent. In addition, increased carbohydrate concentration does not necessarily imply increased productivity if stress simultaneously suppresses biomass formation.

For nutritional and biotechnological applications, future studies should therefore report carbohydrate concentration together with biomass productivity and characterize the molecular structure of the target polysaccharide. This distinction is particularly important when biological activity is claimed, because functional effects demonstrated for a purified polysaccharide cannot automatically be extrapolated to whole diatom biomass.

2.4. Pigments and Antioxidant-Associated Metabolites

Diatoms possess a characteristic pigment system comprising chlorophyll *a*, chlorophyll *c* forms, carotenoids, and xanthophyll-cycle pigments, including fucoxanthin, diadinoxanthin, and diatoxanthin. These pigments participate primarily in light harvesting, photoprotection, and regulation of photosynthetic energy transfer. Their nutritional and commercial significance arises from the combination of high pigment diversity and the reported biological activities of selected carotenoids.

Fucoxanthin has attracted particular attention because experimental studies have associated it with antioxidant, anti-inflammatory, metabolic, and other potential bioactivities. However, the abundance of fucoxanthin is physiologically regulated and should not be assumed to increase uniformly under environmental stress. Light intensity, nutrient status, temperature, and growth phase can modify pigment allocation, while severe stress may impair photosynthetic activity and reduce pigment synthesis. Interpretation should therefore consider pigment ratios, particularly fucoxanthin relative to chlorophylls, as well as the simultaneous response of photoprotective xanthophylls.

Comparative studies have reported substantial differences in fucoxanthin productivity among diatom taxa. For example, *Nitzschia laevis* has been reported to achieve approximately 6.21 mg L⁻¹ day⁻¹ under a particular cultivation regime [14]. Such productivity values are useful for evaluating production potential but should not be directly compared with pigment concentrations expressed as percentage dry weight or mg g⁻¹ biomass. A meaningful comparison requires normalization to a common metric and consideration of cultivation conditions and growth rate.

Diatom antioxidant activity has also been evaluated using chemical assays such as DPPH, ABTS, and FRAP [8]. These assays provide evidence of radical-scavenging or reducing capacity but should not be interpreted as direct measures of *in vivo* antioxidant efficacy. Differences in solvent polarity, extraction temperature, extraction duration, cell-disruption method, pigment stability, and co-extracted compounds can substantially affect assay outcomes. Moreover, chemical antioxidant capacity does not establish physiological efficacy in humans or animals. Thus, the nutritional relevance of diatom pigments should be evaluated across three distinct levels: pigment abundance and productivity, chemical antioxidant activity, and biological efficacy. Evidence at one level should not automatically be extrapolated to the next.

2.5. Minerals, Micronutrients, and Biosilica

Diatom biomass also contains macro- and micronutrients including phosphorus, potassium, magnesium, calcium, iron, zinc, and other trace elements [10,18]. These constituents contribute to cellular metabolism and may enhance the nutritional value of biomass when present at physiologically appropriate concentrations. However, mineral composition is strongly dependent on species, growth medium, environmental availability, cultivation system, and the extent to which extracellular or frustule-associated material is retained during biomass harvesting.

Silicon is particularly distinctive because it is incorporated into the hydrated silica matrix of the diatom frustule. Silicon availability influences frustule formation and, in many silicifying species, is closely associated with cell-cycle progression and cellular architecture. The presence of biosilica therefore differentiates diatom biomass from many other microalgal feedstocks, while simultaneously creating challenges for biomass processing and assessment of nutrient accessibility. Mineral composition should also be considered from a food- and feed-safety perspective. Diatoms can accumulate elements from their surrounding environment, and the distinction between an essential micronutrient and a potentially toxic element depends on concentration, chemical form, bioavailability, and exposure route. Consequently, nutritional characterization should not be restricted to desirable minerals; it should also include appropriate contaminant screening where biomass is intended for human or animal consumption [24,25].

At present, mineral and trace-element datasets remain considerably less comprehensive than those available for proteins, lipids, and pigments, particularly for freshwater, benthic, and non-model taxa. Future investigations should therefore combine elemental profiling with measurements of bioavailability, chemical speciation where relevant, cultivation-source effects, and contaminant accumulation. Such information is necessary for distinguishing nutritionally valuable mineral content from potential safety risks.

2.6. Integrative Interpretation of Diatom Nutritional Composition

The nutritional characteristics of diatoms are best understood as a multidimensional phenotype generated by interactions among taxonomic identity, environmental conditions, physiological state, cultivation strategy, and analytical methodology. High protein biomass does not necessarily indicate superior protein quality; increased total lipid does not necessarily correspond to greater EPA productivity; elevated carbohydrate content does not establish functional polysaccharide activity; and high pigment abundance or chemical antioxidant capacity does not by itself demonstrate nutritional efficacy.

Accordingly, comparative nutritional assessment should report biochemical composition together with cultivation conditions, growth phase, biomass productivity, target-metabolite productivity, analytical methodology, and, where relevant, measures of bioavailability and safety. This condition-resolved framework is essential for identifying taxa and cultivation strategies suited to specific applications and provides a more robust basis for evaluating diatoms as nutritional resources than comparison of isolated biochemical percentages.

The Table 1 presents the relative biochemical composition of selected commercially and ecologically significant diatom species, including *Phaeodactylum tricornutum*, *Skeletonema costatum*, *Chaetoceros calcitrans*, *Thalassiosira pseudonana*, *Navicula* sp., and *Odontella aurita*. Comparative distributions of proteins, lipids, carbohydrates, ash/minerals, and pigments demonstrate substantial interspecific variability in metabolic allocation and nutritional architecture. The elevated protein content, EPA-rich lipid fractions, and diverse pigment composition observed across these taxa highlight the considerable potential of diatoms as sustainable sources of nutritionally and industrially valuable biomolecules for applications in aquaculture, nutraceuticals, pharmaceuticals, and biotechnology. Overall, the nutritional value of diatoms is determined by the combined contribution of proteins, essential amino acids, omega-3 fatty acids, functional polysaccharides, bioactive pigments, and micronutrients. However, reported biochemical compositions vary substantially among species, strains, cultivation systems, and analytical methodologies. Consequently, direct comparisons among studies should be interpreted cautiously. Future efforts should emphasize standardized nutritional assessment protocols and comparative analyses across taxonomically diverse diatom groups to facilitate their effective utilization in food, feed, nutraceutical, and biotechnology sectors.

Table 1. Reported biochemical composition, cultivation context and biotechnological relevance of selected diatom taxa.

Species/Taxon	Cultivation/ Environmental Context	Growth Phase/ Physiological State	Protein (% DW)	Lipid (% DW)	Major Fatty Acids/Target Lipids	Major Pigments	Major Carbohydrates/ Polysaccharides	Biomass or Target-Product Productivity	Nutritional/ Biotechnological Significance	Reference
<i>Phaeodactylum tricornutum</i>	Laboratory and pilot-scale photobioreactor cultivation; composition varies with cultivation conditions	Study-specific; report the growth phase where available	37.8–43.3 *	24.5–30.0 *	EPA; palmitic acid (16:0); other fatty acids, depending on strain and conditions	Fucoxanthin; chlorophyll <i>a</i>	Chrysolaminarin and other storage carbohydrates	Productivity must be reported separately from biomass composition; provide the cultivation-specific rate when available	Model diatom for protein- and EPA- containing biomass, pigment production and integrated bioprocessing	[14,17,26]
<i>Nitzschia laevis</i>	Controlled laboratory cultivation; nutritional composition and product formation depend on culture conditions	Study-specific; distinguish growth phase and heterotrophic or autotrophic conditions	Study- specific; insert a value only where the original source reports it	Study- specific; insert a value only where the original source reports it	EPA and other PUFAs	Fucoxanthin and chlorophylls, where reported	Polysaccharide composition requires species- and study-specific confirmation	EPA or total-PUFA productivity should be reported with units and cultivatin conditions; retain the fucoxanthin productivity value only after checking the original result	Potential source of EPA and other valuable biomolecules; supports evaluation of target-product productivity alongside biomass composition	[27]
<i>Chaetoceros calcitrans</i>	Laboratory cultivation and aquaculture- oriented culture systems	Condition- dependent; nutrient availability and physiological state affect composition	Reported values vary among studies; no single range assigned here	Reported values vary among studies; no single range assigned here	EPA and other long-chain PUFAs, depending on culture conditions	Fucoxanthin and other carotenoids, where measured	Storage carbohydrates; specific polysaccharide identity should be source-verified	Report the measured biomass or metabolite productivity from the cited cultivation study	Important live-feed microalga in aquaculture; relevant for essential fatty acids and nutritional quality	[28]
<i>Skeletonema costatum</i>	Marine laboratory and aquaculture cultivation	Condition- dependent; nutrient status and growth phase may influence lipid allocation	Reported values vary among studies; no universal range assigned	Reported values vary among studies; no universal range assigned	EPA and other PUFAs	Fucoxanthin and chlorophylls, where reported	Storage carbohydrates; avoid assigning a specific glucan without evidence	Report study- specific biomass and EPA productivity separately	Relevant to aquaculture nutrition and the production of PUFA-containing biomass	[28]
<i>Thalassiosira weissflogii</i>	Controlled marine cultivation; growth and composition depend on medium and environmental conditions	Study-specific	Not established from the currently matched references	Not established from the currently matched references	Fatty-acid profile requires a species- specific source	Chlorophylls and fucoxanthin, where measured	Carbohydrate identity and abundance require a species-specific source	No comparable productivity value assigned	Potential research organism for studying diatom physiology and biochemical allocation; nutritional ranking requires verified composition data	[29]

Table 1. Cont.

Species/Taxon	Cultivation/ Environmental Context	Growth Phase/ Physiological State	Protein (% DW)	Lipid (% DW)	Major Fatty Acids/Target Lipids	Major Pigments	Major Carbohydrates/ Polysaccharides	Biomass or Target-Product Productivity	Nutritional/ Biotechnological Significance	Reference
<i>Thalassiosira pseudonana</i>	Defined laboratory/model cultivation systems	Nutrient- and physiological- state dependent	Not established from the currently matched references	Not established from the currently matched references	EPA and other fatty acids, where reported	Chlorophyll <i>a</i> , chlorophyll <i>c</i> and fucoxanthin, where measured	Chrysolaminarin, subject to source verification for the particular claim	Report study- specific productivity were measured	Model diatom for research on nutrient responses, metabolism and carbon allocation; not a substitute for species-specific nutritional assessment	[30–32]
<i>Navicula</i> spp.	Benthic freshwater or marine habitats; species-level ecological and biochemical differences are substantial	Species-, nutrient- and growth-state dependent	Not established as a defensible genus-wide range	Not established as a defensible genus-wide range	Species-specific fatty-acid profiles; PUFAs were demonstrated	Chlorophylls and carotenoids, where measured	Extracellular polymeric substances (EPS) or storage polysaccharides only where directly reported	Standardized cross-study productivity data not established from the listed references	Potential source of benthic diatom biomass and extracellular products; nutritional or industrial potential must be evaluated at species or strain level	[33–35]
<i>Cyclotella</i> spp.	Predominantly freshwater or brackish habitats, depending on species; cultivation conditions vary	Species-, nutrient- and growth-phase dependent	Not established as a defensible genus-wide range	Not established as a defensible genus-wide range	Fatty-acid profile requires species-specific evidence	Chlorophylls and carotenoids, where measured	Storage polysaccharides require species- specific confirmation	No comparable productivity value assigned	Underexplored group for comparative freshwater diatom research; applications require verified species- level biochemical data	[36]

Note: DW, dry weight; EPA, eicosapentaenoic acid; PUFA, polyunsaturated fatty acid; EPS, extracellular polymeric substances. * The range 37.8–43.3% protein and 24.5–30.0% lipid summarizes values reported in separate studies of *P. tricornutum*; these are not replicate measurements or a universal species range. The 37.8% protein and 24.5% lipid values are associated with the pilot-scale study [17], whereas the higher protein value and the remaining range endpoints must be checked against their respective original sources. Do not infer target-product productivity from percentage composition. Values should be compared only when the analytical basis, cultivation conditions, growth phase and productivity units are sufficiently comparable. “Not established” indicates that a defensible, directly matched value has not been confirmed from the references currently available; it does not mean the taxon lacks the relevant biochemical component.

3. Metabolic Plasticity, Nutritional Trade-Offs, and Translational Challenges in Diatoms

The nutritional composition of diatoms is not adequately represented by fixed species-level ranges because their biochemical phenotype varies with strain identity, environmental conditions, physiological state, and cultivation history. Carbon assimilation, nitrogen and phosphorus metabolism, silicon-dependent growth, lipid remodeling, pigment regulation, and storage-product accumulation respond dynamically to these factors. This metabolic plasticity offers opportunities to direct cellular metabolism toward selected products, but it also limits comparisons among studies conducted under different conditions.

A fundamental distinction must be made between biomass composition and production performance. Protein or lipid expressed as a percentage of dry weight (%DW) describes the relative abundance of a component, whereas biomass productivity and volumetric target-productivity quantify production over time and culture volume. A culture with a high lipid percentage may consequently yield less lipid per unit volume or time if lipid accumulation coincides with substantial growth inhibition. Nutritional composition and process performance should therefore be evaluated as related but distinct outcomes.

3.1. Metabolic Trade-Offs and Carbon–Nutrient Allocation

Diatom metabolism allocates assimilated carbon, energy, and nutrients among cell division, maintenance, photosynthetic machinery, membrane synthesis, storage, and stress responses. Under nutrient-replete conditions, resources support protein synthesis, nucleic-acid production, and cellular proliferation. When nutrient availability becomes limiting, carbon assimilation and nutrient-dependent biosynthesis may become uncoupled, changing the relative allocation of carbon to storage compounds and other stress-associated metabolites.

Nitrogen deprivation can suppress protein synthesis and cell proliferation while promoting neutral-lipid and triacylglycerol (TAG) accumulation in some diatoms. However, increased total lipid content does not necessarily indicate improved nutritional lipid quality. Nutrient stress may alter the balance between storage and membrane lipids and change the relative abundance of individual polyunsaturated fatty acids (PUFAs). The optimal cultivation condition therefore depends on the intended endpoint, such as total lipid accumulation, TAG production, preservation of membrane-associated PUFAs, or eicosapentaenoic acid (EPA) productivity [10,18].

Similar trade-offs can affect carbohydrates and pigments. Storage-carbohydrate accumulation may increase the proportion of carbohydrate in biomass without increasing overall biomass productivity. Changes in photoprotective pigments may support acclimation to environmental stress but do not necessarily translate into greater biomass or pigment yield. These responses demonstrate why individual biochemical components should be evaluated alongside growth and production metrics.

3.2. Species- and Strain-Specific Nutritional Strategies

Diatom taxa differ in biochemical composition and in their capacity to produce target compounds under particular cultivation conditions. Comparative studies must therefore distinguish differences in composition from differences in productivity. For example, Lu et al. (2024) reported approximately 43.3% protein in *Phaeodactylum tricornutum* and investigated biochemical and product-related differences among *P. tricornutum*, *Nitzschia laevis*, and *Isochrysis galbana* [14]. Because *I. galbana* is a haptophyte rather than a diatom, its results should be treated as a comparative microalgal reference, not as evidence of nutritional variation among diatoms. The reported protein value and any productivity estimates should be retained only after their analytical basis, units, and original source have been verified.

Species-specific responses are also shaped by ecological and physiological context. Planktonic, benthic, freshwater, marine, estuarine, and polar diatoms encounter different regimes of irradiance, nutrient availability, salinity, temperature, and substrate conditions. Their responses to these factors cannot be assumed to be uniform. Moreover, results obtained from one strain should not automatically be generalized to all members of the same species.

Research has concentrated on a relatively small group of established laboratory models, including *P. tricornutum*, *Thalassiosira pseudonana*, *Skeletonema* species, and selected *Chaetoceros* taxa. The nutritional and biotechnological potential of many freshwater and benthic lineages remains less comprehensively characterized. Broader strain screening is therefore needed to identify organisms that combine desirable biochemical characteristics with environmental tolerance, reproducible performance, and suitability for scalable cultivation.

3.3. Nitrogen, Phosphorus, and Silicon: Endpoint-Dependent Responses

Nutrient manipulation is widely investigated as a means of modifying diatom biochemical composition, but its effects depend on the species, strain, stress intensity, exposure duration, and growth phase. Nitrogen limitation may increase total lipid or TAG content while reducing biomass formation. Its effects on EPA and other PUFAs are less predictable: these fatty acids may be maintained, redistributed among lipid classes, or reduced under different conditions. Accordingly, nitrogen deprivation should not be described as a universal strategy for increasing omega-3 production.

Interpretation requires separate reporting of total lipid content, TAG content, EPA proportion, EPA concentration, biomass productivity, and EPA volumetric productivity wherever these measurements are available. Two-stage cultivation, in which biomass is first accumulated under growth-supporting conditions and metabolite production is subsequently induced, may help balance biomass formation and product accumulation. Its practical advantage, however, depends on whether increased product yield compensates for additional cultivation, nutrient-management, energy, and harvesting requirements.

Phosphorus limitation can affect growth and membrane composition because phosphorus is required for nucleic acids, energy metabolism, and phospholipid synthesis. Silicon has a distinct role in diatoms because frustule formation is linked to cell-cycle progression and cellular development. Changes in silicon availability can therefore affect division and growth, with subsequent consequences for biomass production and physiological state. These nutrients should be considered separately because their metabolic roles and limiting effects are not interchangeable.

3.4. Light, Temperature, and Photophysiological Regulation

Light availability influences photosynthetic carbon fixation, energy conversion, and photoprotection. Its effects on growth and biochemical composition are not necessarily linear: increasing irradiance may support photosynthesis under light-limited conditions, whereas excessive exposure can cause photoinhibition and oxidative stress.

Fucoxanthin responses illustrate this complexity. Diatoms regulate their fucoxanthin–chlorophyll antenna systems and xanthophyll-cycle pigments, including diadinoxanthin and diatoxanthin, to balance light harvesting and photoprotection. Changes in irradiance may alter pigment concentrations and pigment ratios, but high-light exposure should not be assumed to increase absolute fucoxanthin content. Studies should distinguish pigment concentration per unit biomass from volumetric pigment productivity and report the relevant cultivation conditions.

Temperature interacts with irradiance and nutrient availability and can influence photosynthetic efficiency, enzyme activity, membrane properties, and fatty-acid composition. Acclimation within a strain's tolerance range may produce responses different from those associated with severe thermal stress. Consequently, potential effects of climate-related warming on nutritional composition should be evaluated through interacting environmental factors rather than temperature alone.

3.5. Growth Phase and Biomass Productivity

Biochemical composition also varies over the cultivation cycle. During active growth, resources are allocated to cell division, protein synthesis, photosynthetic machinery, and membrane formation. As cultures approach stationary phase, nutrient depletion and changes in cellular demand may alter the relative abundance of storage lipids, carbohydrates, and stress-associated metabolites.

A higher percentage of a target component in stationary-phase biomass does not necessarily indicate greater production efficiency. The same culture may have accumulated biomass more slowly or may produce less target compound per unit volume and time. Nutritional studies should therefore report growth phase, cultivation duration, biomass concentration, and the productivity metric alongside compositional measurements whenever possible.

For process optimization, the preferred harvest point is not necessarily the time of maximum component percentage. It is the point at which biomass accumulation, target-product yield, product quality, cultivation duration, and downstream-processing requirements collectively provide an acceptable production outcome.

3.6. From Metabolic Plasticity to Translational Performance

Translating laboratory findings into larger-scale cultivation requires evidence that biochemical composition and productivity can be maintained under less controlled conditions. Laboratory systems can regulate irradiance, temperature, nutrient supply, salinity, pH, and gas transfer more consistently than large cultivation systems, where spatial and temporal gradients may affect growth and metabolism.

Banskota et al. (2026) reported protein and lipid contents of 37.8% and 24.5%, respectively, for *Phaeodactylum tricornutum* biomass cultivated in photobioreactors described as having a 1000-L scale [17,21]. These results may provide evidence of protein- and lipid-rich biomass production beyond small laboratory cultures. Before making a stronger claim about scale-up, however, the original study should be checked for the reactor's nominal capacity and actual working volume, cultivation duration, replication, analytical basis, and reported performance metrics. The carbohydrate value of 19.4% should be included only if verified in the original study and confirmed to use a comparable dry-weight basis. Claims concerning essential amino-acid adequacy, EPA production, and fucoxanthin content should likewise be limited to the endpoints actually measured.

Compositional results from a larger reactor do not, on their own, demonstrate commercial feasibility, consistent batch performance, or the economic viability of an integrated biorefinery. These outcomes require additional evidence concerning reproducibility, culture stability, contamination control, harvesting, biomass processing, product recovery, and production costs.

Overall, the biotechnological value of a diatom depends on more than its maximum reported biochemical content. It also depends on whether the target product can be generated reproducibly at an acceptable productivity and quality under scalable cultivation conditions. Future studies should integrate strain-level physiological characterization with process optimization and, where appropriate, techno-economic and life-cycle assessments. Reporting composition, biomass productivity, target-product productivity, and product-quality attributes separately would improve cross-study comparisons and help distinguish promising laboratory phenotypes from candidates with credible translational potential.

4. Advanced Approaches for Nutritional Characterization of Diatoms

Reliable nutritional characterization of diatoms requires standardized cultivation, appropriate biomass processing, validated analytical methods, and cautious interpretation of the resulting data. Because biochemical composition can vary with species, strain, growth phase, cultivation conditions, and analytical procedure, measurements obtained under different experimental conditions should not be treated as directly comparable without considering these factors. Analytical approaches should therefore distinguish biomass composition from metabolite productivity, molecular characterization, and demonstrated nutritional functionality. Table 2 summarizes the principal analytical approaches and their applications and limitations.

For diatoms, sample preparation also requires consideration of the silica-containing frustule, which can affect biomass disruption and analyte recovery. The effectiveness of cell disruption should be evaluated for the target species and analyte rather than assumed from the use of a standard extraction protocol. Where relevant, extraction recovery, analytical blanks, replicate measurements, calibration procedures, and quality-control samples should be reported to support comparisons among studies.

Table 2. Analytical approaches for determining the biochemical composition, molecular characteristics, and nutritional attributes of diatom biomass.

Analytical Category	Method or Approach	Information Obtained	Important Limitation or Consideration
Cultivation and biomass preparation	Defined culture medium; controlled cultivation; documented harvesting and storage	Provides experimental context for interpreting biomass composition	Cultivation metadata describe experimental conditions, not nutritional attributes themselves.
Cell disruption and extraction	Bead beating, high-pressure homogenization, or other validated disruption procedures; analyte-specific extraction	Releases intracellular compounds and supports recovery of target analytes	Frustule resistance and cell properties may affect disruption and extraction recovery. Validate for the species and target analyte.
Crude protein estimation	Kjeldahl or Dumas nitrogen analysis followed by a stated nitrogen-to-protein conversion factor	Estimates crude protein from total nitrogen	May include non-protein nitrogen; results depend on the conversion factor and should not be treated as a direct measurement of intact protein.
Protein-specific assays	Bradford, Lowry, or bicinchoninic acid (BCA) colorimetric assays	Estimates protein concentration based on assay-specific chemical responses	Assays differ in response to proteins and susceptibility to interference; results may not be directly comparable across methods.
Amino-acid composition	Hydrolysis followed by HPLC, UPLC, or LC-MS	Quantifies amino acids and helps characterize essential amino-acid composition	Hydrolysis and derivatization conditions affect recovery; certain amino acids require specialized procedures.
Protein identification	Proteomics using mass-spectrometric workflows	Identifies proteins and supports investigation of protein-level responses	Protein identification or abundance does not directly establish total protein content, digestibility, or nutritional quality.
Total lipid extraction	Bligh–Dyer, Folch, or another validated solvent-extraction procedure	Estimates recoverable total lipid	Recovery depends on sample preparation, solvent system, and biomass properties; frustule-related limitations should be considered.

Table 2. Cont.

Analytical Category	Method or Approach	Information Obtained	Important Limitation or Consideration
Fatty-acid profiling	FAME preparation followed by GC–FID or GC–MS	Determines fatty-acid composition, including EPA where present	Relative fatty-acid percentages, absolute biomass concentrations, and volumetric productivity are different metrics.
Lipid-class and molecular profiling	LC–MS-based lipidomics or other validated lipid-class methods	Characterizes lipid classes and molecular species	Results depend on extraction, separation, ionization, identification criteria, and analytical coverage.
Total carbohydrate estimation	Phenol–sulfuric acid assay or another validated total-carbohydrate method	Estimates total carbohydrate concentration	Does not identify individual sugars or establish polysaccharide structure or biological activity.
Monosaccharide and polysaccharide characterization	Hydrolysis followed by chromatographic analysis; complementary structural spectroscopy where appropriate	Determines monosaccharide composition and supports structural characterization	Hydrolysis may alter or incompletely recover particular constituents; total carbohydrate results cannot substitute for structural analysis.
Pigment characterization	Spectrophotometry; HPLC or LC–MS for compound-specific analysis	Estimates total pigment content or quantifies individual pigments	Bulk spectrophotometry is less compound-specific; compound identification and quantification require suitable validation.
Antioxidant activity	DPPH, ABTS, FRAP, or ORAC assays	Measures assay-specific chemical antioxidant activity	Results from different assays are not directly interchangeable and do not establish clinical benefit.
Mineral and elemental analysis	Acid digestion followed by ICP–MS, ICP–OES, or atomic absorption spectroscopy	Quantifies selected macroelements, micronutrients, and potentially toxic elements	Requires appropriate detection limits, calibration, quality control, and interpretation in relation to intended use and safety.
Integrated molecular characterization	Genomics, transcriptomics, proteomics, metabolomics, lipidomics, and fluxomics	Supports investigation of molecular composition and candidate metabolic pathways	Molecular associations require validation against measured biochemical traits; computational predictions are not equivalent to experimental confirmation.
Nutritional and functional validation	Digestibility, bioavailability, stability, contaminant screening, and application-specific testing	Assesses attributes relevant to the intended food or feed application	No single compositional assay establishes overall nutritional quality, safety, or commercial suitability.

Notes: Cultivation conditions and sample-processing procedures are included as factors affecting analytical interpretation, not as nutritional attributes. Nitrogen-based crude-protein estimates are distinct from colorimetric protein assays and amino-acid profiling. All composition and productivity values should specify their units and reporting basis. Method selection should be supported by appropriate validation and quality-control procedures. Abbreviations: BCA, bicinchoninic acid; DPPH, 2,2-diphenyl-1-picrylhydrazyl; EPA, eicosapentaenoic acid; FAME, fatty-acid methyl ester; FRAP, ferric-reducing antioxidant power; GC–FID, gas chromatography–flame-ionization detection; GC–MS, gas chromatography–mass spectrometry; HPLC, high-performance liquid chromatography; ICP–MS, inductively coupled plasma–mass spectrometry; ICP–OES, inductively coupled plasma–optical emission spectrometry; LC–MS, liquid chromatography–mass spectrometry; ORAC, oxygen radical absorbance capacity; UPLC, ultra-performance liquid chromatography.

4.1. Standardized Cultivation and Sample Preparation

Standardized cultivation and sample preparation are essential for obtaining reproducible nutritional profiles. Culture medium, temperature, irradiance, photoperiod, salinity, nutrient availability, aeration, cultivation duration, and growth phase should be documented when reporting biochemical composition. The use of defined media, such as Guillard's f/2 medium where appropriate, facilitates experimental reproducibility, although medium selection must reflect the physiological requirements of the species under investigation [37].

Biomass should be harvested at a clearly defined growth phase, separated from the culture medium using a suitable method, and processed under conditions that minimize degradation of proteins, lipids, pigments, and other labile compounds. Sample storage duration, temperature, drying method, moisture content, and extraction conditions should also be reported. Results should be expressed on a clearly defined basis, such as percentage of dry weight (%DW), concentration per unit culture volume (mg L⁻¹), or volumetric productivity (mg L⁻¹ day⁻¹). These metrics represent different outcomes and should not be used interchangeably.

4.2. Protein and Amino-Acid Characterization

Protein assessment involves several analytical approaches that differ in their measurement principles. Kjeldahl and Dumas methods estimate total nitrogen, which is subsequently converted to crude protein using a specified nitrogen-to-protein conversion factor. These measurements do not directly quantify intact protein and may include contributions from non-protein nitrogen. By contrast, Bradford, Lowry, and bicinchoninic acid (BCA) assays estimate protein concentration through colorimetric responses, but their results can depend on protein composition, assay chemistry, extraction conditions, and interfering substances. Consequently, values obtained using nitrogen-based and protein-specific methods should not be considered equivalent without methodological qualification.

Amino-acid profiling provides complementary information on protein composition and nutritional relevance. Following appropriate hydrolysis, amino acids can be separated and quantified using high-performance liquid chromatography (HPLC), ultra-performance liquid chromatography (UPLC), or liquid chromatography–mass spectrometry (LC–MS). Hydrolysis and derivatization procedures must be selected carefully because some amino acids, including tryptophan and sulfur-containing amino acids, may require specialized analytical treatment. Total amino-acid composition can help identify essential amino acids and potential limitations in the nutritional profile, but it does not independently establish protein digestibility or bioavailability.

Proteomic approaches extend this analysis by identifying proteins, peptides, and proteins associated with particular physiological processes. However, proteomic abundance is not a direct substitute for total protein content or amino-acid composition. For nutritional applications, analytical results should therefore be interpreted alongside essential amino-acid profiles, digestibility evidence, and the intended use of the biomass.

4.3. Lipidomics and Fatty-Acid Profiling

Lipid characterization requires distinguishing total lipid content, lipid-class composition, individual fatty-acid abundance, and production productivity. Conventional solvent-extraction procedures, including the Bligh–Dyer and Folch methods, are widely used to recover lipids, although extraction efficiency depends on the biomass matrix, solvent system, and sample-disruption procedure. The rigid frustule and differences in cellular organization may influence recovery, making validation of the extraction procedure important for diatom biomass.

Fatty-acid profiles are commonly determined after conversion of fatty acids to fatty-acid methyl esters (FAMES), followed by gas chromatography with flame-ionization detection (GC–FID) or gas chromatography–mass spectrometry (GC–MS). Liquid chromatography–mass spectrometry can provide complementary information on intact lipid classes and molecular species. These techniques answer different analytical questions: FAME analysis characterizes fatty-acid composition, whereas lipidomics can resolve lipid classes and molecular species.

Results should distinguish the percentage of a fatty acid within total fatty acids from its concentration per unit dry biomass and its volumetric productivity. For example, a high EPA proportion does not necessarily indicate high EPA production per culture volume if biomass productivity is low. Accordingly, comparisons among diatom strains should consider both composition and production metrics, together with cultivation conditions and extraction recovery [7,10].

4.4. Carbohydrate and Polysaccharide Characterization

Carbohydrate analysis should distinguish total carbohydrate concentration from the identity, structure, and functionality of individual carbohydrate fractions. The phenol–sulfuric acid assay is commonly used to estimate total carbohydrate content, but it does not identify individual sugars or establish polysaccharide structure. More detailed characterization may involve hydrolysis followed by chromatographic analysis of monosaccharides, together with complementary spectroscopic techniques where structural information is required.

Chrysolaminarin is an important storage glucan in diatoms, while extracellular polysaccharides may contribute to cell-surface interactions and other biological functions. However, the presence of a carbohydrate fraction alone does not establish prebiotic, antioxidant, immunomodulatory, or other health-related effects. Such claims require evidence from appropriate functional assays, with stronger conclusions requiring validated biological models and, where relevant, *in vivo* or human studies. Differences in extraction, hydrolysis, molecular size, monosaccharide composition, and purification can also influence the properties attributed to a polysaccharide preparation [38].

4.5. Pigment Characterization and Antioxidant Assays

Diatoms contain photosynthetic and photoprotective pigments, including chlorophylls, β -carotene, diadinoxanthin, and fucoxanthin. Pigments may be quantified using spectrophotometric methods or separated using HPLC and related chromatographic techniques. Chromatographic separation is particularly useful when individual pigments must be quantified in a complex extract, whereas bulk spectrophotometric measurements provide less compound-specific information.

Fucoxanthin has attracted interest because of its reported biological activities, but its presence in diatom biomass should not be interpreted as evidence of a demonstrated health benefit. Likewise, assays such as DPPH, ABTS, ferric-reducing antioxidant power (FRAP), and oxygen radical absorbance capacity (ORAC) measure different aspects of chemical antioxidant activity under defined assay conditions. Their results are not necessarily interchangeable and do not establish antioxidant efficacy in humans [39].

Integrating pigment measurements with metabolomic or transcriptomic data may help investigate pigment biosynthesis and regulation. Nevertheless, mechanistic conclusions require evidence linking molecular changes to measured pigment concentrations and, where claimed, to functional outcomes.

4.6. Elemental and Mineral Profiling

Elemental analysis can characterize macroelements, micronutrients, and potentially harmful contaminants in diatom biomass. Inductively coupled plasma–mass spectrometry (ICP–MS), inductively coupled plasma–optical emission spectrometry (ICP–OES), and atomic absorption spectroscopy are commonly used following appropriate sample digestion. Method selection depends on the elements of interest, required detection limits, and sample matrix.

Nutritional interpretation requires distinguishing essential elements from potentially toxic elements and considering their concentrations relative to the intended application. The detection of an element does not establish its bioavailability, and accumulation of an essential element does not automatically make biomass suitable for food or feed. Biomass intended for nutritional applications should therefore be assessed for relevant contaminants, with analytical quality assurance and suitable reporting limits. Environmental origin and cultivation medium should also be considered when evaluating the suitability of biomass for downstream use [40].

4.7. Multi-Omics and Systems-Level Characterization

Genomics, transcriptomics, proteomics, metabolomics, lipidomics, and fluxomics provide complementary information on the molecular processes underlying diatom metabolism. Transcriptomics identifies changes in gene expression, proteomics characterizes proteins, metabolomics measures small-molecule profiles, and lipidomics resolves lipid-related molecular features. Fluxomics can provide information about metabolic pathway activity when supported by suitable experimental designs and modelling approaches.

Integrating these datasets can help identify candidate pathways and regulatory mechanisms associated with the production of proteins, lipids, pigments, and other metabolites. However, changes in transcript abundance do not necessarily translate into corresponding changes in protein abundance, metabolite concentration, or production rate. Similarly, associations identified through multi-omics analyses should not be interpreted as causal mechanisms without additional validation.

A robust systems-level analysis should therefore combine molecular datasets with directly measured biochemical traits, clearly defined cultivation conditions, and appropriate statistical validation. Computational modelling and machine-learning approaches may support prediction and experimental prioritization, but their reliability depends on data quality, sample size, independent validation, and the range of conditions represented in the training data [10,41].

4.8. From Analytical Measurements to Nutritional Quality

The nutritional interpretation of diatom biomass requires integration of analytical composition with evidence of biological availability, safety, and application-specific performance. Proximate composition, amino-acid profiles, fatty-acid composition, pigments, carbohydrates, and elemental measurements provide complementary rather than interchangeable information. A high concentration of a particular constituent does not, by itself, establish overall nutritional quality.

For food and feed applications, compositional measurements should be supplemented, as appropriate, by digestibility studies, contaminant screening, stability assessments, and evaluation of the intended product. *In Vitro* functional assays can provide preliminary evidence of biological activity but should be distinguished from animal or human evidence. Similarly, promising laboratory-scale composition does not independently demonstrate economic feasibility or suitability for commercial production.

Standardized reporting should therefore include the analytical method, sample preparation and disruption procedures, calibration and quality-control measures, units and reporting basis, biological and technical replication, and relevant cultivation metadata. This approach improves comparability among studies and helps identify which diatom strains and cultivation systems merit further nutritional, safety, and scale-up evaluation.

5. Linking Nutritional Profiling to Environmental Stress Responses

Diatom nutritional composition should be interpreted as a dynamic phenotype generated by interactions among taxonomic identity, habitat, nutrient availability, light, temperature, growth phase and cultivation history, rather than as a fixed species characteristic. This metabolic plasticity is particularly important because environmental stress can alter the partitioning of cellular carbon, nitrogen, phosphorus and reducing power among

proteins, membrane lipids, storage compounds, pigments and carbohydrates. Consequently, changes in metabolite concentration do not necessarily represent improvements in nutritional productivity; an increase in the cellular concentration of a target compound may occur simultaneously with reduced growth and biomass formation. A mechanistic interpretation of nutritional profiles therefore requires the joint consideration of metabolite concentration, biomass productivity, growth rate and physiological status.

5.1. Species-Specific Variability and Functional Diversity

Diatoms should not be regarded as a nutritionally uniform resource, because biochemical composition, physiological plasticity, and the magnitude of stress-induced metabolic responses vary substantially among species and strains. Differences in carbon allocation, nutrient assimilation, lipid remodeling, pigment regulation, carbohydrate storage, and silicon metabolism arise from the interaction between taxonomic identity and environmental history. Consequently, the nutritional phenotype measured in a given diatom culture represents the outcome of both intrinsic metabolic characteristics and extrinsic cultivation conditions rather than a fixed species-level trait. This distinction is important when comparing diatoms for food, feed, nutraceutical, or biotechnological applications, because a high concentration of a target compound under one experimental condition does not necessarily translate into superior biomass productivity or process performance under another. The representative diatom taxa shown in Figure 5 illustrate the ecological and taxonomic diversity considered in nutritional and biotechnological research, encompassing marine planktonic, freshwater, benthic and polar forms. These examples provide ecological context for comparing species-specific physiological responses; however, their inclusion does not imply that all taxa have been equally characterized in terms of nutritional composition or biotechnological potential.



Figure 5. Representative and ecologically important diatom species used in nutritional and biotechnological studies. (Source: Authors' conceptual synthesis based on literature reviewed in this study).

The commonly studied model diatom *Phaeodactylum tricornutum* illustrates both the opportunities and limitations of species-focused research. Its relatively well-characterized genome, established genetic transformation systems, metabolic flexibility, and capacity to accumulate valuable lipids have made it an important platform for studying carbon partitioning, EPA production, pigment metabolism, and metabolic engineering. However, its extensive representation in the literature should not be interpreted as evidence that its nutritional responses are representative of diatoms as a whole. Diatoms occupy highly diverse ecological niches, and species adapted to benthic, freshwater, polar, coastal, or nutrient-variable environments may exhibit substantially different physiological strategies.

Marine planktonic genera such as *Chaetoceros*, *Skeletonema*, and *Thalassiosira* provide an important contrasting group. Their rapid growth, capacity to exploit fluctuating nutrient conditions, and production of

proteins and long-chain polyunsaturated fatty acids have supported their use in aquaculture and investigations of nutritionally valuable biomass. Nevertheless, their nutritional suitability should be evaluated using multiple endpoints rather than total lipid or protein concentration alone. In aquaculture, for example, the practical value of a species depends on the combination of biomass productivity, fatty-acid composition, digestibility, trophic compatibility, and consistency of biochemical composition under production conditions. Thus, the designation of a species as nutritionally “superior” requires consideration of both biochemical quality and biomass yield [42].

Differences become particularly evident when lipid accumulation and EPA production are considered simultaneously. Oleaginous or stress-responsive taxa such as *Nitzschia* and selected *Navicula* species can exhibit substantial lipid accumulation under nutrient stress, but an increase in total lipid concentration does not necessarily correspond to an increase in EPA productivity. Nitrogen deprivation, for example, can promote carbon transfer from protein synthesis toward storage compounds, particularly triacylglycerol (TAG), while simultaneously reducing cell division and altering the relative contribution of EPA-containing membrane lipids. Consequently, lipid content, TAG content, EPA percentage of total fatty acids, absolute EPA concentration, and volumetric EPA productivity should be treated as distinct endpoints. This distinction is essential for identifying genuinely productive strains rather than simply stress-tolerant phenotypes.

Cold-adapted diatoms provide another example of functional specialization. Species such as *Fragilariopsis cylindrus* have evolved membrane-remodeling strategies that maintain cellular function under low temperatures, including adjustments in the degree of fatty-acid unsaturation. Such responses can increase the relative importance of polyunsaturated fatty acids for membrane homeostasis and may enhance the nutritional value of biomass for particular applications. However, cold adaptation should not automatically be equated with high industrial productivity. A strain capable of maintaining a high PUFA proportion at low temperature may simultaneously exhibit slower growth, lower biomass concentration, or greater cultivation costs. Therefore, the industrial relevance of cold-adapted diatoms depends on the balance between biochemical quality, growth kinetics, environmental requirements, and process energy demand. Environmental factors including temperature, phosphorus availability, and species identity can interact to produce divergent PUFA responses, further emphasizing the need for species-specific evaluation.

Freshwater and benthic diatoms further expand the functional diversity of the group. Genera such as *Cyclotella*, *Navicula*, and *Gomphonema* occur across a broad range of freshwater habitats and are frequently used in ecological assessment because their distributions and abundances respond to nutrient availability, organic enrichment, pH, conductivity, and other environmental variables. Their ecological importance, however, should not be interpreted as evidence of a uniformly distinctive nutritional composition. In particular, benthic growth, biofilm formation, extracellular polymeric substance (EPS) production, and exposure to fluctuating microenvironmental conditions can alter carbon allocation and biochemical composition. Thus, the nutritional properties of benthic taxa should be evaluated within the context of growth form, substrate association, environmental conditions, and physiological state rather than extrapolated from planktonic cultures. These examples indicate that taxonomic identity and ecological adaptation are important explanatory variables, but neither can substitute for direct biochemical evidence. Table 3 summarizes representative ecological and functional groups while distinguishing their potential relevance from conclusions that require further experimental validation.

The same caution applies to carbohydrate-rich or EPS-producing diatoms. Chrysolaminarin represents an important intracellular carbon reserve in many diatoms, whereas extracellular polysaccharides contribute to adhesion, biofilm formation, protection from environmental stress, and interactions with surrounding microorganisms. However, neither “ β -glucan-rich” nor “EPS-producing” is sufficient to establish functional or nutraceutical value. Biological activity depends on structural characteristics including molecular weight, degree and pattern of branching, monosaccharide composition, sulfation, conformation, and purification history. Consequently, taxonomic assignment alone cannot be used to predict the bioactivity of a diatom-derived polysaccharide. Compound-specific characterization is required before claims concerning immunomodulatory, antioxidant, antimicrobial, or prebiotic effects can be generalized.

Pigment metabolism similarly demonstrates the importance of ecological and physiological context. Fucoxanthin is a major photosynthetic carotenoid in many diatoms, but its cellular concentration and productivity are strongly influenced by light availability, nutrient status, growth phase, and species identity. Low-light conditions can favor fucoxanthin accumulation as part of the light-harvesting apparatus, whereas prolonged or excessive irradiance may cause photoinhibition and substantial pigment loss. In *P. tricornutum*, for example, high-light exposure has been associated with reductions in chlorophyll and fucoxanthin together with broader metabolic remodeling, illustrating why the simplistic assumption that environmental stress invariably increases fucoxanthin is inappropriate. Accordingly, pigment concentration should be interpreted alongside biomass productivity, pigment-to-chlorophyll ratios, photoprotective responses, and the severity and duration of the imposed stress [43].

Silica-associated functional diversity also warrants consideration when comparing diatom groups. The siliceous frustule is a defining structural feature of diatoms and imposes distinctive requirements for silicon uptake, intracellular processing, and cell-cycle coordination. Differences in silicon demand and frustule formation can consequently influence growth and elemental stoichiometry. Large-frustule genera such as *Coscinodiscus* and *Actinocyclus* may therefore possess characteristics of interest for biomaterials research; however, silica abundance or frustule size alone does not establish suitability for nanobiotechnology. Applications based on biosilica require additional assessment of frustule architecture, pore structure, surface chemistry, mechanical properties, extraction procedures, reproducibility, and scalability [38].

Table 3. Functional diversity across representative diatom ecological groups.

Ecological/ Functional Group	Representative Taxa	Principal Physiological or Ecological Characteristics	Nutritional/ Biochemical Relevance	Potential Application	Critical Interpretation
Marine planktonic	<i>Chaetoceros</i> , <i>Thalassiosira</i> spp.	Rapid growth, bloom formation, efficient nutrient utilization	Protein, EPA and other PUFAs; variable pigment and carbohydrate profiles	Aquaculture, nutraceutical biomass	Nutritional value depends strongly on strain, growth phase and cultivation conditions
Marine model	<i>Phaeodactylum tricornutum</i>	High physiological plasticity; extensive genomic and genetic resources	EPA-rich lipids, pigments, storage compounds and proteins	EPA production, metabolic engineering, biotechnology	Well characterized but should not be considered representative of all diatoms
Oleaginous/stress- responsive	<i>Nitzschia</i> spp.; selected <i>Navicula</i> spp.	Strong metabolic responses to nutrient and environmental stress	Enhanced neutral lipid/TAG accumulation under selected conditions; PUFA production	Lipid bioprocessing, nutraceutical research	High lipid concentration may occur with reduced growth and does not necessarily indicate high EPA productivity
Coastal/bloom- forming	<i>Skeletonema chaetoceros</i> spp.	Rapid population growth and adaptation to fluctuating coastal conditions	Proteins, EPA/PUFAs and photosynthetic pigments	Aquaculture and biomass production	Performance should be evaluated using both nutritional quality and biomass productivity
EPA/PUFA- focused	<i>Odontella aurita</i> , selected <i>Thalassiosira</i> spp.	Capacity for long- chain PUFA synthesis	EPA and other nutritionally relevant PUFAs	Omega-3 production and nutraceutical research	PUFA percentage and volumetric productivity are separate performance metrics
Polar/cold-adapted	<i>Fragilariopsis cylindrus</i> , <i>Chaetoceros neogracile</i>	Cold adaptation and membrane homeostasis under low temperature	High degree of fatty- acid unsaturation in appropriate physiological contexts	Omega-3 researches, cold- adaptation studies	High PUFA proportion may be accompanied by lower growth and productivity at low temperature
Freshwater planktonic	<i>Cyclotella meneghiniana</i> , <i>Asterionella formosa</i>	Seasonal dynamics and adaptation to freshwater nutrient regimes	Variable protein, lipid, pigment and carbohydrate composition	Ecological monitoring; emerging biomass resource	Nutritional potential remains less characterized than that of marine model taxa
Benthic/epiphytic	<i>Navicula</i> , <i>gomphonema</i> spp.	Biofilm formation, substrate association and fluctuating microhabitats	Variable lipids, carbohydrates and EPS	Ecological monitoring; selected bioproduct applications	Composition is highly dependent on habitat and physiological state
Large/frustule- dominated marine taxa	<i>Coscinodiscus</i> , <i>actinocyclus</i> spp.	Large siliceous frustules and distinctive structural architectures	Biosilica and associated biochemical components	Biomaterials and frustule-based technologies	Silica richness alone does not establish nanobiotechnology suitability

Species-level differences are further amplified by strain-level variation. Closely related strains can differ in growth rate, nutrient requirements, lipid partitioning, pigment abundance, stress tolerance, and target-metabolite productivity even when cultured under nominally identical conditions. Such variation may reflect differences in genotype, acclimation history, epigenetic regulation, or previous environmental selection. Comparative genomic, transcriptomic, proteomic, and metabolomic approaches can help identify the molecular basis of these phenotypes, but omics-level differences should ultimately be linked to experimentally measured biomass productivity and target-compound yields. Multi-omics data therefore provide mechanistic resolution rather than an independent measure of industrial performance.

Taken together, the functional diversity of diatoms indicates that species selection should be treated as a multidimensional optimization problem rather than a search for a universally superior taxon. A strain selected for

EPA production may not be optimal for protein recovery; a strain exhibiting high TAG accumulation may suffer substantial growth penalties; a cold-adapted taxon may possess desirable PUFA characteristics but require greater energy input for cultivation; and a silica-rich species may offer biomaterial advantages without necessarily providing superior nutritional value. Consequently, rational strain selection should integrate taxonomic identity, ecological adaptation, growth kinetics, biomass productivity, target-metabolite productivity, biochemical quality, cultivation requirements, and downstream processing constraints.

This species- and strain-dependent framework provides an essential basis for interpreting the environmental responses discussed in the following subsections. Rather than assuming a universal diatom response to nutrient or physical stress, subsequent analysis should therefore distinguish taxon $\times$ environment interactions, because the same perturbation can produce contrasting outcomes in protein synthesis, TAG accumulation, EPA retention, pigment remodeling, carbohydrate storage, and growth. Such an approach shifts nutritional optimization from simple enhancement of individual biochemical constituents toward integrated optimization of biomass quality and productivity under defined cultivation conditions.

5.2. Carbon–Nitrogen Allocation under Nitrogen Limitation

Nitrogen availability exerts a strong influence on diatom biochemical composition because nitrogen is required for amino acids, proteins, nucleic acids, photosynthetic proteins and other nitrogen-containing cellular components. Under nitrogen limitation, reduced nitrogen assimilation and protein biosynthesis can increase the relative availability of fixed carbon for storage metabolism. In susceptible taxa, this is accompanied by enhanced synthesis and accumulation of neutral lipids, particularly triacylglycerols (TAGs), together with reductions in protein content [13,19]. The response represents a resource-allocation strategy rather than a universal enhancement of lipid productivity.

This distinction is particularly important for nutritionally valuable omega-3 fatty acids. Nitrogen deprivation can increase total lipid or TAG concentration while simultaneously reducing growth rate and altering membrane-lipid composition. Consequently, a higher lipid percentage on a dry-weight basis does not necessarily translate into higher EPA productivity on a culture-volume or time basis. EPA accumulation is also dependent on species, strain, growth phase and severity and duration of nitrogen stress. Thus, *Phaeodactylum tricornutum* and *Nitzschia laevis* may respond differently to comparable nutrient regimes, and even within a single species, moderate nutrient stress may produce a different biochemical outcome from prolonged nitrogen starvation. This distinction is critical when evaluating diatoms for nutraceutical or biofuel applications because maximum metabolite concentration and maximum volumetric productivity may occur under different physiological conditions.

At the metabolic level, nitrogen stress is also associated with broader reorganization of carbon and nitrogen metabolism rather than an isolated lipid response. The ornithine–urea cycle, amino-acid metabolism and carbon fixation pathways contribute to redistribution and recycling of cellular nitrogen and carbon, allowing diatoms to maintain essential metabolism during nutrient scarcity [44]. Therefore, nitrogen limitation should be considered a coordinated metabolic state involving reduced investment in nitrogen-rich biomass and altered allocation toward storage and stress-maintenance pathways, rather than simply a lipid-induction strategy.

5.3. Phosphorus Limitation and Membrane-Lipid Remodeling

Phosphorus limitation produces a distinct metabolic response because phosphorus is required for nucleic acids, ATP and membrane phospholipids. Diatoms can respond by increasing phosphorus-acquisition and recycling mechanisms while reducing cellular phosphorus demand. One important consequence is membrane-lipid remodeling, in which phosphorus-containing phospholipids can be replaced or supplemented by non-phosphorus-containing lipid classes. In *Thalassiosira pseudonana*, for example, phosphorus limitation has been associated with changes in phospholipid and non-phosphorus lipid pools, demonstrating that lipid accumulation under nutrient stress involves changes in lipid class composition, not simply an increase in total lipid.

This distinction has direct implications for nutritional profiling. An increase in total lipid under phosphorus stress should not automatically be interpreted as enhanced nutritional value because membrane remodeling may alter the relative abundance of phospholipids, neutral storage lipids and specific PUFA-containing lipid classes. Recent work on the freshwater diatom *Achnanthes minutissimum* further demonstrates that phosphorus availability is closely connected with intracellular polyphosphate dynamics and cellular phosphorus conservation [45,46]. Thus, phosphorus stress provides an example of why nutritional assessment should resolve lipid classes and molecular species, rather than relying exclusively on gravimetric total-lipid measurements.

5.4. Silicon Availability, Frustule Formation and Metabolic Allocation

Silicon represents a diatom-specific environmental constraint because silicic acid is required for biosilica deposition and frustule formation. Silicon availability is therefore closely linked to cell-cycle progression, cellular morphology and biomass production. Silicon limitation can interrupt normal valve formation and constrain cell division, thereby changing the relationship between carbon fixation and biomass accumulation. Mechanistic modelling has shown that cellular silicon is strongly associated with the balance between silicon uptake and growth, while silicon availability also influences cellular C: Si, N: Si and P: Si relationships.

The nutritional consequences of silicon stress are therefore indirect and context dependent. Reduced cell division can result in a physiological state in which carbon assimilation continues despite constrained biomass production, potentially modifying the partitioning of carbon among storage and structural compounds. Recent transcriptomic evidence from *Skeletonema dohrnii* further indicates that silicon starvation can produce coordinated changes involving frustule formation, cell-cycle regulation, carbon metabolism and lipid metabolism rather than a simple increase in one nutritional component [47].

Accordingly, silicon should be incorporated into nutritional optimization strategies not merely as a requirement for frustule synthesis but as a regulator connecting cell-cycle progression, elemental stoichiometry and metabolic allocation. This is particularly relevant when comparing planktonic centric diatoms with benthic and epiphytic taxa that experience substantially different microscale silicon environments.

5.5. Light Intensity and Pigment–Lipid Trade-Offs

Light availability represents another major determinant of diatom biochemical composition because photosynthetic carbon fixation and cellular redox balance are directly coupled to irradiance. Moderate changes in irradiance can modify photosynthetic investment, pigment composition, antioxidant capacity and carbon allocation. However, the relationship between irradiance and fucoxanthin is not unidirectional. Fucoxanthin participates in light harvesting through fucoxanthin–chlorophyll protein complexes, but prolonged or excessive irradiance can induce photoprotective acclimation involving reductions in light-harvesting pigments.

For example, prolonged high-light exposure in *P. tricornutum* produced substantial declines in fucoxanthin and chlorophyll, followed by pigment recovery during subsequent recovery conditions. This demonstrates that severe high-light stress should not be interpreted as a universal stimulus for fucoxanthin accumulation. Nutritional assessment should instead consider absolute pigment concentration, pigment productivity, fucoxanthin-to-chlorophyll ratios and the duration and severity of light exposure. Such an approach avoids conflating photoprotective acclimation with increased nutraceutical productivity.

Light responses may also interact with nutrient status. For example, nutrient limitation can alter the capacity of cells to synthesize photosynthetic proteins and pigments, whereas high irradiance can increase oxidative pressure when cellular antioxidant and repair systems become limiting. Consequently, light and nutrient effects should be considered as interacting environmental drivers rather than independent variables.

5.6. Temperature and Fatty-Acid Remodeling

Temperature influences membrane homeostasis and therefore can alter the degree of fatty-acid unsaturation required to maintain appropriate membrane fluidity. Lower temperatures frequently favour increased incorporation of unsaturated fatty acids in membrane lipids, whereas warmer conditions may promote greater relative saturation. However, increased PUFA content under cold conditions should not be interpreted automatically as increased EPA productivity. The magnitude and direction of EPA responses depend on species, strain, growth rate, acclimation history and the interaction between temperature and nutrient/light availability.

This distinction is particularly important when comparing diatoms occupying contrasting thermal environments. Polar and cold-water taxa may possess strong constitutive or inducible mechanisms for maintaining membrane functionality under low temperatures, whereas tropical, temperate, freshwater and coastal taxa may exhibit different acclimation strategies. Consequently, temperature-driven PUFA responses should be evaluated using both relative fatty-acid composition and absolute EPA productivity, rather than percentage composition alone [48].

5.7. Taxonomic and Habitat Context as Modifiers of Stress Responses

Environmental responses cannot be generalized across diatoms solely on the basis of taxonomic class or broad habitat category. Planktonic centric diatoms, pennate benthic taxa, epiphytic species, freshwater forms and polar or cold-water taxa occupy different ecological niches and experience contrasting nutrient, irradiance,

temperature and hydrodynamic regimes. Their biochemical responses consequently reflect both physiological acclimation and longer-term ecological adaptation.

For example, *Thalassiosira*, *Chaetoceros* and *Skeletonema* are widely investigated in planktonic and aquaculture contexts, whereas genera such as *Navicula*, *Gomphonema* and *Fragilariopsis* represent a broader range of ecological settings, from benthic freshwater habitats to cold-water environments. Their inclusion in nutritional comparisons can help broaden the evidence base beyond intensively studied model species. However, statements such as “marine diatoms are lipid-rich” or “freshwater and benthic diatoms are carbohydrate-rich” should be avoided unless supported by standardized comparative datasets. Differences in culture medium, salinity, temperature, irradiance, growth phase and analytical methodology may substantially influence biochemical composition alongside taxonomic identity.

The selected taxa and their broad habitat associations are illustrated schematically in Figure 6. This representation provides ecological context rather than quantitative evidence of species distributions or biochemical differences. Nutritional comparisons should therefore remain anchored to studies reporting identifiable taxa, experimental conditions, analytical methods and comparable biochemical measurements.

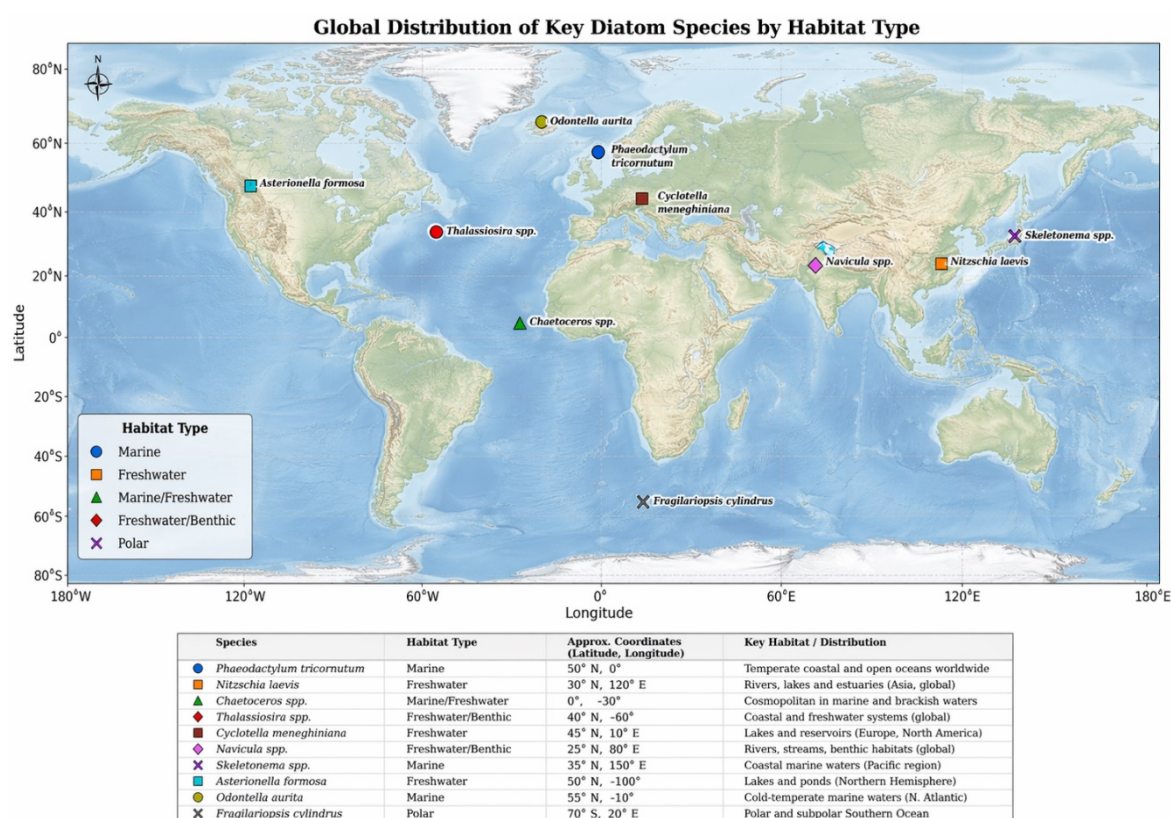


Figure 6. Illustrative geographic representation of selected diatom taxa across major habitat types. Locations are schematic and indicate broad habitat associations; they do not represent exhaustive or quantitative species-distribution records.

5.8. From Stress Response to Nutritional Optimization

Collectively, these observations indicate that environmental stress can create trade-offs among biomass formation, cellular maintenance and target-metabolite accumulation. Nitrogen or phosphorus limitation may promote storage-lipid accumulation under some conditions while reducing growth; silicon limitation can constrain cell division and alter carbon allocation; high irradiance can trigger photoprotective responses without consistently increasing fucoxanthin; and temperature shifts can modify membrane polyunsaturated fatty acid (PUFA) composition without necessarily increasing volumetric eicosapentaenoic acid (EPA) productivity. Thus, an increase in the percentage of a target compound does not, by itself, demonstrate improved overall productivity or nutritional quality.

Nutritional optimization should instead identify cultivation conditions under which target-compound concentration, biomass productivity and the desired biochemical profile are jointly favourable. A potential strategy is two-stage or temporally controlled cultivation, in which biomass is first generated under growth-supporting

conditions and subsequently exposed to a controlled nutritional or environmental stimulus to redirect metabolism. Research on *Phaeodactylum tricornutum* illustrates how cultivation conditions can influence biomass and the accumulation of compounds such as EPA, fucoxanthin and carbohydrates. However, the effectiveness of such strategies depends on the strain, cultivation conditions, target product and balance between biomass loss and metabolite accumulation; it should therefore be evaluated experimentally rather than assumed. Overall, the relationship between environmental conditions and nutritional composition is better understood as a dynamic resource-allocation process than as a linear “stress → metabolite increase” response. This framework provides a basis for selecting candidate species, designing cultivation experiments and interpreting biochemical profiles across marine, freshwater, benthic, epiphytic and polar diatoms.

5.9. Emerging Global Market Trends and Commercialization Potential of Diatom-Derived Products

The global transition toward sustainable bio-based industries has substantially accelerated interest in diatom-derived products due to their multifunctional applications in nutraceuticals, pharmaceuticals, aquaculture, cosmetics, renewable energy, and environmental biotechnology. In recent years, commercialization efforts have increasingly shifted from laboratory-scale feasibility studies toward industrial-scale production systems, supported by advances in cultivation technologies, biorefinery integration, and growing consumer demand for sustainable natural products. Market analyses conducted between 2024 and 2026 indicate that microalgae-derived compounds, particularly omega-3 fatty acids, carotenoids, bioactive polysaccharides, and renewable biofuels, are experiencing significant global expansion driven by health-conscious consumer behavior, climate-related sustainability initiatives, and regulatory support for low-carbon bioeconomy sectors [49]. Among commercially relevant products, omega-3 polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA), represent one of the most rapidly expanding sectors in diatom biotechnology. Marine diatoms such as *Phaeodactylum tricornutum*, *Chaetoceros calcitrans*, and *Thalassiosira weissflogii* have demonstrated substantial EPA productivity and are increasingly explored as sustainable alternatives to fish-derived omega-3 supplements. Recent industrial assessments suggest that rising concerns regarding overexploitation of marine fisheries, combined with increasing demand for plant-based nutritional products, are accelerating investment in microalgal omega-3 production systems. Additionally, advances in metabolic engineering and precision cultivation have improved lipid productivity and enhanced the economic feasibility of algal nutraceutical production. Fucoxanthin and other carotenoid-rich extracts derived from diatoms are also gaining increasing commercial significance due to their antioxidant, anti-inflammatory, anti-obesity, and neuroprotective properties. Recent market evaluations indicate that the global demand for fucoxanthin-based nutraceutical formulations is expanding rapidly, particularly across Asian, European, and North American health supplement industries [50]. The growing preference for naturally derived bioactive compounds over synthetic additives has further stimulated research into large-scale cultivation of pigment-rich diatom strains.

In the renewable energy sector, diatoms continue to attract attention as promising feedstocks for third-generation biofuels because of their rapid growth rates, high lipid productivity, and capacity for cultivation on non-arable land using saline or wastewater systems. Recent techno-economic analyses have emphasized the potential of integrated biorefinery systems capable of simultaneous biofuel production and recovery of high-value co-products, thereby improving commercial viability. Emerging studies have demonstrated that hydrothermal liquefaction and thermochemical conversion of diatom biomass can efficiently generate bio-crude while simultaneously recovering silica-based nanomaterials for industrial applications. Such integrated valorization strategies are increasingly viewed as essential for overcoming the economic limitations traditionally associated with algal biofuel systems.

The aquaculture sector also represents a major commercial driver for diatom biotechnology. Diatoms remain indispensable components of hatchery systems due to their high nutritional quality, digestibility, and essential fatty acid composition. The demand for nutritionally suitable live-feed organisms is an important consideration in sustainable aquaculture, particularly in marine hatcheries where diatoms contribute essential fatty acids to the diets of larval fish and shellfish. Recent research has examined controlled photobioreactor cultivation to improve diatom biomass production and regulate biochemical composition. For example, *Phaeodactylum tricornutum* cultivated in a flat-plate airlift photobioreactor demonstrated the potential to tailor biomass composition through controlled nutrient conditions [50], while preliminary work on automated cultivation of *Chaetoceros muelleri* investigated the relationship between harvesting schedules, biomass yield and fatty-acid composition [51]. As illustrated in Figure 7, these studies highlight the potential of controlled cultivation systems for producing more consistent diatom biomass, although further validation is required to establish their scalability and reliability for aquaculture live-feed production.

Technological innovations are further accelerating the industrial scalability of diatom-based systems. The integration of artificial intelligence (AI), machine learning, automation, and omics-guided metabolic optimization is enabling real-time monitoring and precision control of cultivation parameters. Recent studies emphasize that digital bio-manufacturing platforms can significantly improve biomass productivity, nutrient utilization efficiency, and metabolite accumulation while reducing operational costs [52]. In parallel, developments in closed photobioreactor systems, biofilm-based cultivation, and wastewater-integrated production models are improving sustainability and reducing freshwater dependency. Regulatory and policy frameworks are also playing an increasingly important role in promoting commercialization pathways for diatom-derived products. Several countries have introduced bioeconomy strategies emphasizing sustainable biomass utilization, carbon-neutral industrial systems, and renewable bioproduct development. Furthermore, expanding regulatory approvals for novel algal food ingredients and nutraceutical compounds are creating favorable conditions for industrial investment and market penetration.

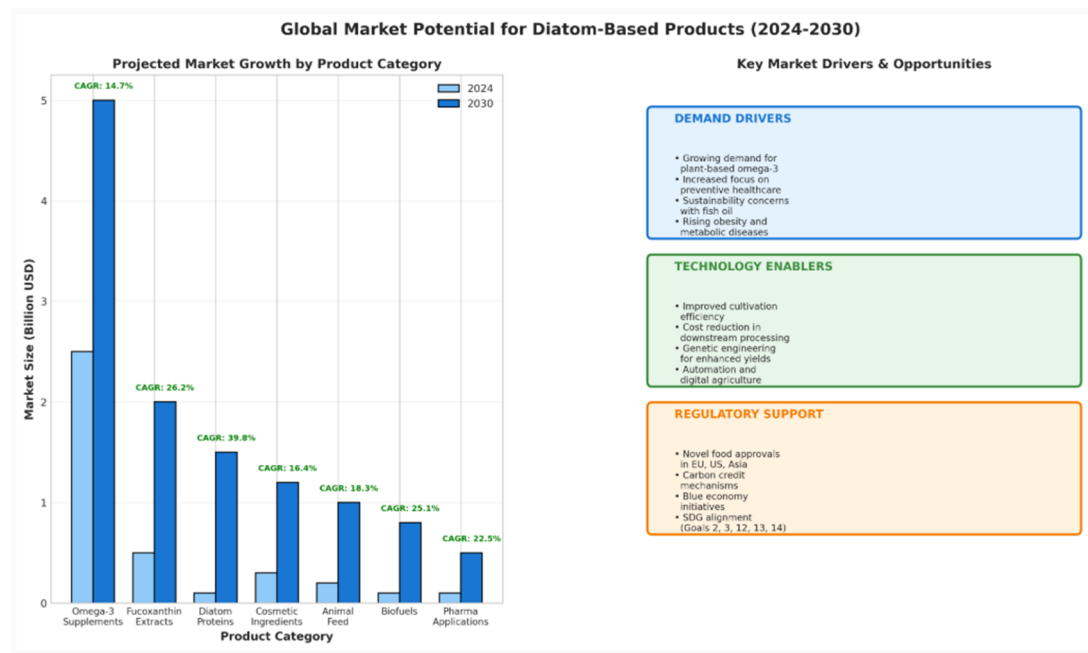


Figure 7. Global market potential and commercialization drivers of diatom-based products (2024–2030).

The alignment of algal biotechnology with global sustainability agendas, including the United Nations Sustainable Development Goals (SDGs), further strengthens the long-term commercial outlook for diatom-based industries.

Despite these promising developments, commercialization remains constrained by challenges related to large-scale cultivation costs, harvesting efficiency, product standardization, and economic competitiveness relative to conventional industrial products. Nevertheless, recent market projections suggest substantial growth potential between 2024 and 2030, particularly in sectors associated with omega-3 supplements, functional foods, pharmaceuticals, cosmetics, animal feed, and renewable energy systems. Collectively, these trends indicate that diatoms are transitioning from niche research organisms toward commercially viable bioresources with significant relevance to the future global bioeconomy.

6. Advanced Applications, Sustainable Bioeconomy, and Climate-Resilient Diatom Biotechnology

Diatoms offer opportunities to link biological carbon fixation with the production of commercially valuable biomolecules and more resource-efficient biotechnological processes. Through CO₂ fixation and biomass generation, they can provide feedstock for applications such as aquaculture, nutraceuticals, pigments, and integrated biorefinery systems. Their contribution to a sustainable bioeconomy, however, depends on cultivation efficiency, resource use, downstream processing, and the effective utilization of residual biomass. In parallel, understanding how diatom growth and biochemical composition respond to changing environmental conditions is important for developing climate-responsive cultivation strategies. These interconnected pathways, from CO₂ fixation to bioproduct generation and the potential contribution of diatom biotechnology to a sustainable bioeconomy and climate resilience, are summarized conceptually in Figure 8.

The application landscape of diatom biotechnology is moving beyond the conventional use of whole biomass toward the selective exploitation of defined biochemical, structural, and physiological properties. Diatoms have long been investigated as sources of aquaculture feed, nutritional lipids, pigments, and bioenergy feedstocks, while advances in metabolomics, systems biology, cultivation engineering, biomaterials science, and process optimization have expanded the range of potential applications [10,14]. This transition, however, should not be interpreted simply as an increase in the number of proposed applications. Rather, it represents a shift toward function-oriented bioprocessing, in which strain characteristics, cultivation conditions, metabolic state, product composition, and downstream recovery are considered as interconnected determinants of product quality and process performance. Importantly, most emerging applications remain at different stages of technological maturity, and promising laboratory-scale properties do not necessarily translate into economically or environmentally viable processes. Consequently, the future development of diatom biotechnology will depend not only on discovering additional bioactive compounds but also on improving compositional consistency, process control, product safety, recovery efficiency, and whole-system sustainability.

Role of Diatoms in Sustainable Bioeconomy and Climate Resilience

From Nature's Biofactories to a Sustainable Future



Figure 8. Diatoms as key drivers of sustainable bioeconomy and climate resilience: from CO₂ fixation to bioproduct generation. Conceptual synthesis illustrating the links between biological carbon fixation, diatom biomass production, value-added bioproducts, resource recovery, and climate-responsive biotechnology.

6.1. Precision Nutrition and Functional Biomolecules

The nutritional application of diatoms is increasingly shifting from the production of undifferentiated biomass toward the generation of biomass with more predictable biochemical characteristics. Diatom species and strains differ substantially in the relative abundance and composition of proteins, long-chain polyunsaturated fatty acids (LC-PUFAs), pigments, sterols, antioxidants, and other bioactive constituents [10,19]. Controlled manipulation of environmental and nutritional conditions can modify these profiles, providing a basis for producing biomass tailored to specific nutritional or functional requirements. Such approaches may be relevant to aquaculture feeds, functional foods, nutraceutical formulations, and other applications in which a defined biochemical composition is preferable to simply maximizing total biomass production.

However, the concept of precision nutrition should be interpreted cautiously. Enhancement of a target metabolite may occur at the expense of growth rate, cellular stability, or the accumulation of other nutritionally relevant compounds. Moreover, the magnitude and direction of these responses are strongly strain- and condition-dependent. Therefore, increasing the concentration of an individual PUFA, pigment, or antioxidant does not necessarily translate into improved nutritional performance at the product level. Bioavailability, chemical stability

during processing and storage, interactions among co-occurring compounds, and dose-dependent biological effects also require consideration. Evidence for health-related benefits frequently remains stronger at the biochemical, cellular, or experimental level than in controlled human interventions. Future development should consequently combine strain selection and cultivation control with compositional standardization, bioavailability assessment, toxicological evaluation, and appropriately designed clinical studies before health-oriented claims can be generalized.

6.2. Bioactive Metabolites and Health-Oriented Biotechnology

The functional potential of diatoms extends beyond established compounds such as EPA and fucoxanthin. Diatom metabolomes contain diverse lipids, sterols, oxylipins, phenolic-associated compounds, polysaccharides, pigments, and antioxidant metabolites that may contribute to biological activity [16,17]. Increasingly, this diversity is being considered as a network of interacting metabolites rather than as a collection of isolated molecules. Such a perspective is important because the biological activity of a diatom extract may reflect additive or synergistic interactions among several constituents rather than the effect of the most abundant compound alone [8].

Nevertheless, chemical identification and preliminary bioactivity are insufficient to establish a therapeutically or nutritionally relevant function. Considerable uncertainty remains regarding the reproducibility of metabolite profiles among strains, the influence of cultivation conditions, extraction selectivity, compound stability, mechanisms of action, bioavailability, and effective concentrations. Consequently, future health-oriented applications should establish a traceable relationship among strain identity → cultivation conditions → chemical profile → extraction method → biological mechanism → dose–response relationship. Standardized analytical workflows, mechanistic studies, toxicological assessment, pharmacokinetic characterization, and well-designed *in vivo* and clinical investigations are therefore required to distinguish promising bioactivity from evidence sufficient for product development.

6.3. Biosilica and Advanced Biomaterial Applications

Diatom frustules represent a structurally distinct class of naturally fabricated biosilica whose species-specific architecture, hierarchical porosity, surface chemistry, and optical properties have attracted interest in materials research. These characteristics have been investigated for applications including drug-delivery systems, biosensors, tissue-engineering scaffolds, bioimaging, photonic structures, adsorption, and catalytic materials [46,52]. The principal attraction of diatom biosilica is not simply its silica composition but the naturally generated nanoscale and microscale architecture that can provide structural features difficult to reproduce using conventional fabrication approaches. Beyond their nutritional and bioactive constituents, diatom biomass and silica-rich frustules provide structurally versatile platforms for environmental applications. Diatom-derived biosilica and functionalized biogenic nanostructures have been investigated for pollutant adsorption, photocatalytic processes, membrane-based treatment and other water-purification strategies, expanding the potential of diatoms from nutritional resources to multifunctional environmental biotechnological materials [53].

At the same time, the functional properties of frustules cannot be assumed to be uniform across diatom taxa. Differences in frustule morphology, pore architecture, surface characteristics, species identity, cultivation history, and post-harvest processing can influence material performance. In addition, the transition from experimentally characterized frustules to standardized biomaterial products requires control over purification, structural integrity, surface modification, reproducibility, and scalability. Biomedical applications impose additional requirements concerning biocompatibility, impurity control, degradation behavior, and regulatory safety. Thus, future research should move from demonstrating isolated material properties toward establishing quantitative relationships between taxonomic/strain identity, frustule architecture, processing conditions, and application-specific performance.

6.4. Environmental Biotechnology and Resource Recovery

The capacity of diatoms to assimilate dissolved nutrients and interact with contaminants provides opportunities for integrating biomass production with wastewater treatment and resource recovery [54]. In such systems, nitrogen, phosphorus, carbon, and other recoverable resources may be incorporated into biomass while photosynthetic activity contributes to treatment processes. This coupling is attractive because it potentially links environmental remediation with the generation of biomass that can subsequently enter material or bioproduct pathways.

However, environmental treatment should not automatically be equated with sustainable biomass production. Wastewater composition can vary substantially over time and may contain contaminants that compromise biomass quality or restrict downstream applications. Biomass produced from contaminated streams may therefore be unsuitable for food, feed, nutraceutical, or pharmaceutical uses, even when pollutant removal efficiency is high. Pretreatment requirements, harvesting costs, seasonal changes, contaminant fate, and disposal or valorization of

the resulting biomass can also influence the overall environmental performance of the system. Future studies should therefore evaluate not only removal percentages but also contaminant mass balance, nutrient recovery efficiency, biomass quality, downstream fate, energy demand, and life-cycle impacts. This distinction is particularly important when environmental remediation and production of high-value products are proposed within the same process.

6.5. Integrated Biorefineries and Circular Bioeconomy

The development of integrated diatom biorefineries provides a potential route for improving biomass utilization by recovering multiple products rather than relying on a single commodity. Depending on species and cultivation conditions, potential product streams may include proteins, LC-PUFAs, pigments, antioxidants, polysaccharides, specialty metabolites, and biosilica [55–57]. Sequential or cascade processing could theoretically improve resource utilization by assigning different biomass fractions to different applications, thereby reducing the amount of residual material requiring disposal.

Nevertheless, multiproduct recovery does not inherently guarantee economic or environmental sustainability. The emerging diatom-based bioeconomy increasingly emphasizes multiproduct utilization, in which nutritionally valuable biomass can be integrated into aquaculture, food/feed, bioproduct and other value chains, thereby improving resource efficiency and supporting circular production systems [58]. Additional fractionation steps may increase solvent use, energy consumption, capital requirements, process complexity, and product losses. The economic value of individual compounds must also be sufficiently high to compensate for their recovery costs. Therefore, the feasibility of a diatom biorefinery should be evaluated using integrated material and energy balances, product yields, market values, process recovery efficiencies, waste generation, and life-cycle indicators rather than inferred solely from the number of recoverable compounds. A scientifically credible biorefinery model should consequently identify which product combinations provide genuine process synergies and which may simply add downstream complexity.

6.6. Diatoms, Carbon Cycling, and Climate Resilience

Diatoms occupy an important position in aquatic carbon cycling because their photosynthetic activity contributes substantially to primary production and, in marine systems, to the biological carbon pump [55]. Carbon export occurs through several interconnected processes, including aggregation, grazing, fecal-pellet formation, particle sinking, and subsequent remineralization. Silica availability and frustule formation can influence particle characteristics and interactions with other components of sinking material, but the magnitude and persistence of carbon export are context-dependent and depend on community composition, nutrient availability, aggregation dynamics, grazing pressure, sinking rates, and remineralization processes [59]. Thus, the relationship between diatom silica production and carbon export should not be represented as a simple or universally proportional enhancement of carbon sequestration.

This distinction is important when considering diatoms within engineered carbon-removal strategies. Their natural contribution to carbon cycling demonstrates biological relevance but does not by itself establish the technical feasibility, permanence, or climate benefit of deliberate large-scale cultivation for carbon removal. Such approaches would require substantial inputs of nutrients and infrastructure and would need to address biomass harvesting, carbon fate, energy requirements, ecological interactions, and long-term storage. A more immediate opportunity may therefore lie in integrating biological carbon fixation with biomass valorization, nutrient recovery, and resource-efficient production systems in which carbon capture provides an additional environmental benefit rather than the sole economic justification.

Diatom physiological plasticity may also contribute to their capacity to respond to changing environmental conditions. Temperature, light availability, nutrient limitation, and carbonate-system changes can alter photosynthesis, membrane lipid composition, carbon allocation, and storage metabolism. For example, nutrient limitation can redirect cellular carbon toward storage compounds, including lipids, while simultaneously reducing biomass productivity. Such responses illustrate an important trade-off: the same metabolic flexibility that permits survival under environmental stress may also produce variability in product yield and composition. Climate-resilient cultivation should therefore prioritize strains and cultivation strategies capable of maintaining acceptable productivity and product quality across realistic environmental fluctuations rather than optimizing performance only under narrowly controlled laboratory conditions.

6.7. Metabolic Engineering and Predictive Diatom Biotechnology

Advances in genome-scale modelling, synthetic biology, gene editing, and systems-level analysis have created opportunities to manipulate metabolic flux toward selected products. *Phaeodactylum tricornutum* is an important model diatom for investigating and engineering lipid and pigment biosynthesis pathways. Research has characterized lipid accumulation under different cultivation conditions and elucidated key steps in the biosynthesis of fucoxanthin and other carotenoids, supporting its potential as a platform for producing high-value bioproducts. Its broader potential as a biotechnological production platform, including for EPA, fucoxanthin and neutral lipids, has also been reviewed by Butler et al. (2020) [60,61]. These approaches may ultimately support more targeted production by linking genetic modification with cultivation control and downstream processing.

However, metabolic engineering in diatoms remains subject to biological constraints that cannot be resolved through pathway modification alone. Redirecting carbon or reducing flux through one pathway can impose metabolic burdens, alter growth, affect stress responses, or compromise cellular stability. Genetic stability and reproducibility during prolonged cultivation and scale-up also require validation. Regulatory considerations and environmental containment become increasingly important as engineered strains move beyond controlled laboratory systems.

Artificial intelligence and machine-learning approaches provide a complementary opportunity by integrating large physiological, environmental, metabolomic, transcriptomic, and cultivation datasets to predict biomass productivity, metabolite accumulation, process instability, or harvesting conditions. Yet predictive performance is inherently dependent on the quality, diversity, and representativeness of the training data. Models developed from a limited number of strains or laboratory conditions may not reliably extrapolate to outdoor cultivation, different geographic environments, or genetically distinct populations. Consequently, AI should be regarded as a decision-support and process-optimization tool rather than a substitute for biological validation. Hybrid approaches combining mechanistic models with data-driven prediction, together with independent validation datasets, may provide a more robust basis for predictive cultivation [62].

6.8. From Biological Potential to Scalable Sustainable Systems

The principal challenge for advanced diatom biotechnology is therefore not the identification of additional potential applications but the conversion of biological diversity into reproducible, scalable, and demonstrably sustainable production systems. Across nutritional, biomedical, biomaterial, environmental, and climate-related applications, several common requirements emerge: reliable strain performance, controlled cultivation, compositional consistency, efficient harvesting and downstream recovery, product safety, and economically realistic processing. These requirements become particularly important when applications depend on high-value compounds whose concentration may be relatively low compared with the total biomass [63].

A sustainable diatom production system should also be evaluated beyond biomass productivity. Water consumption, nutrient inputs, energy demand, land requirements, carbon balance, waste generation, contaminant fate, and downstream processing should be incorporated into system-level assessments. Techno-economic analysis (TEA), life-cycle assessment (LCA), material-flow analysis, and long-term cultivation trials can therefore provide a more rigorous basis for determining whether proposed applications offer genuine environmental or economic advantages [64]. Importantly, these assessments should be performed at the process level because improvements in one stage, such as enhanced metabolite accumulation, may be offset by increased energy requirements for cultivation or extraction.

7. Translational Bottlenecks and the Laboratory-to-Market Gap in Diatom Biotechnology

Despite increasing interest in diatoms as sources of nutraceuticals, aquafeed ingredients, bioactive compounds, pharmaceuticals, and renewable biomaterials, the transition from laboratory-scale demonstration to commercially viable production remains challenging. The central issue is not a lack of biochemical potential, but the difficulty of converting species- and condition-dependent biological performance into reproducible, scalable, economically viable, and regulatory-compliant production processes. Laboratory studies commonly optimize individual physiological or biochemical responses under highly controlled conditions, whereas industrial systems must operate under fluctuating environmental conditions while maintaining biomass productivity, product quality, culture stability, and process efficiency. Consequently, the principal translational bottleneck lies in coordinating biological optimization with process engineering, quality control, economic assessment, and regulatory requirements as depicted in Figure 9 [65,66].

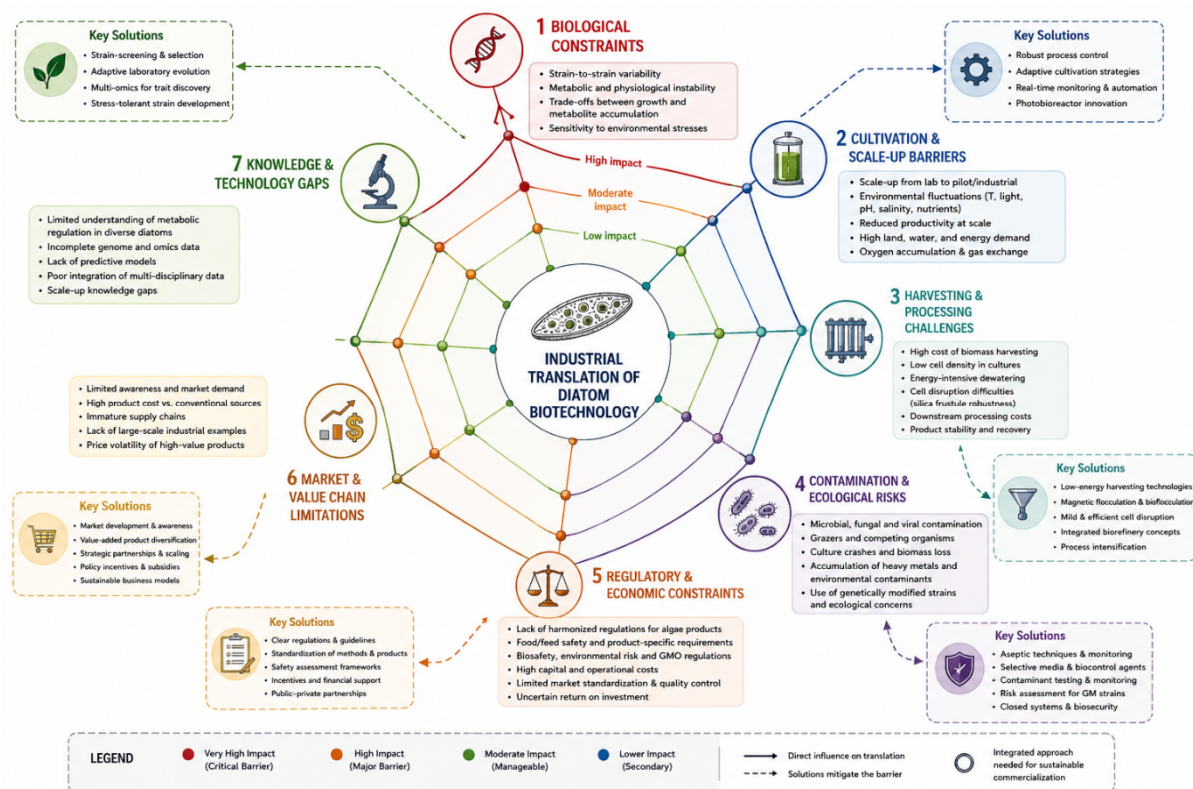


Figure 9. Major translational bottlenecks limiting the industrial commercialization of diatom biotechnology and potential mitigation strategies.

7.1. Productivity–Stability Trade-Off

A fundamental challenge is the trade-off between maximizing biomass productivity and inducing the accumulation of high-value metabolites. Nutrient limitation, altered silica availability, high irradiance, salinity stress, and other environmental perturbations can redirect cellular metabolism toward storage lipids, pigments, antioxidants, or carbohydrates, but may simultaneously reduce growth and photosynthetic performance [10,18]. Thus, the condition producing the highest intracellular concentration of a target compound may not generate the greatest product yield per unit culture volume or reactor area.

This distinction is particularly important for commercial cultivation, where productivity must be evaluated at the process level rather than solely on the basis of metabolite concentration. Strategies that optimize biomass formation during one cultivation phase and metabolite accumulation during a subsequent controlled induction phase may therefore be more appropriate than continuous exposure to severe stress. However, the effectiveness of such two-stage or adaptive strategies remains strongly dependent on species, cultivation platform, and target product. Future optimization should consequently consider biomass productivity, target-product yield, culture stability, energy requirements, and downstream recovery simultaneously rather than maximizing a single biochemical endpoint [67].

7.2. Scale-Up and Process Robustness

The performance of diatom cultures under controlled laboratory conditions does not necessarily translate directly to outdoor ponds or large photobioreactors. At larger scales, fluctuations in temperature, irradiance, pH, dissolved inorganic carbon, nutrient availability, mixing, and gas transfer can alter growth kinetics and cellular resource allocation. These effects are further complicated by species-specific physiological responses, making it difficult to establish cultivation conditions that are universally transferable across diatom taxa [19].

Silica availability represents an additional process consideration that distinguishes diatom cultivation from many other microalgal systems. Because silica is required for frustule formation and cell division, inadequate or poorly controlled silica supply can constrain growth and modify cellular metabolism [46]. At industrial scale, therefore, nutrient delivery cannot be treated simply as a static medium formulation but must be considered in relation to uptake kinetics, biomass density, mixing, and cultivation stage. The translational challenge is consequently not merely to increase reactor volume but to preserve biological performance during scale-up. Robust

process control, adaptive nutrient management, monitoring of physiological indicators, and validation across different cultivation scales will be necessary to determine whether laboratory-optimized traits remain commercially reproducible.

7.3. Biochemical Variability and Product Standardization

The biochemical plasticity that makes diatoms attractive for biotechnology also creates a major challenge for product standardization. Protein, lipid, omega-3 fatty acid, pigment, polysaccharide, sterol, and antioxidant profiles can vary with strain identity, growth phase, nutrient availability, irradiance, temperature, and physiological condition. Consequently, two cultures of the same nominal species may produce substantially different biochemical profiles when cultivated under different conditions. For commercial applications, this variability has direct implications for quality control, efficacy, safety assessment, and regulatory approval. Standardization therefore requires more than reporting the average biochemical composition of a strain. Strain authentication, defined cultivation conditions, harvest-stage specification, validated analytical methods, and acceptable compositional ranges need to be incorporated into production workflows. Real-time monitoring and predictive models may help identify deviations before harvest, but their practical value depends on adequate calibration against experimentally validated product-quality thresholds. Importantly, standardization should also be product-specific. A level of compositional precision appropriate for bulk aquafeed biomass may be insufficient for a purified nutraceutical or pharmaceutical ingredient [68–70]. Thus, future research should move toward application-specific quality specifications rather than assuming that a single biochemical profile can define the quality of all diatom-derived products.

7.4. Harvesting and Downstream Processing Constraints

Advances in biofilm-based cultivation and harvesting technologies may improve the efficiency of diatom biomass production. Attached cultivation systems can facilitate biomass recovery compared with conventional suspended cultures, although performance depends on reactor design, substrate properties, biofilm growth, and operating conditions [71]. Recent experimental work has further investigated temperature-controlled biofilm detachment assisted by ultrasonic vibration, demonstrating the potential of engineered substrates and detachment methods to improve harvesting performance. Nevertheless, the scalability, energy requirements, and economic feasibility of these technologies require further assessment before their benefits can be generalized to commercial diatom production [72]. Subsequent drying, cell disruption, extraction, fractionation, purification, and stabilization can further increase energy and material requirements. The appropriate downstream strategy is strongly dependent on the intended product. Processes suitable for whole-cell aquafeed biomass may be inappropriate for high-purity pigments, omega-3 fatty acids, or pharmaceutical compounds. Accordingly, downstream processing should be incorporated into process design from the beginning rather than treated as a separate post-cultivation step.

Biofilm cultivation, improved harvesting technologies, selective extraction, and integrated processing platforms may reduce resource requirements in specific applications [73]. Nevertheless, their reported advantages should be evaluated using mass balance, energy demand, product recovery, product quality, and techno-economic performance, because laboratory-scale improvements do not necessarily translate into lower costs at commercial scale.

7.5. Culture Stability, Contamination, and Strain Maintenance

Culture stability represents another important barrier, particularly in open or semi-open cultivation systems. Competing microorganisms, grazers, fungi, and other biological contaminants can alter community composition and reduce biomass productivity. The risk may increase when cultures are maintained under strong nutrient or environmental stress, because stress-induced physiological changes can affect cellular resilience.

A related but distinct concern is long-term strain stability. Repeated subculturing and prolonged maintenance may produce physiological drift or changes in growth and metabolite production [74]. Such changes are particularly consequential when a strain has been selected for a specific biochemical phenotype or engineered for enhanced production.

These challenges indicate that strain management should be considered part of the production system rather than simply a culture-maintenance issue. Authentication of production strains, controlled master and working cultures, cryopreservation where appropriate, periodic phenotypic assessment, and genomic or molecular monitoring can help reduce uncertainty. However, the most suitable strategy will depend on the organism, cultivation platform, and intended product.

7.6. The Taxonomic Bottleneck and Strain Discovery Gap

Commercial diatom research remains concentrated on a relatively small number of experimentally tractable taxa, including *Phaeodactylum tricornutum*, *Thalassiosira pseudonana*, and selected *Chaetoceros* species [1,75]. This model-organism bias has facilitated advances in genomics, metabolic engineering, and physiological understanding, but it may also constrain the discovery of strains with superior nutritional composition, environmental tolerance, growth characteristics, or novel bioactive metabolites. Underexplored freshwater, benthic, polar, and extremophilic diatoms may contain traits relevant to cultivation under non-conventional conditions or to the production of compounds that are poorly represented in current model systems. However, taxonomic novelty alone does not establish biotechnological value. New strains must be evaluated through standardized comparative screening that considers growth kinetics, biomass productivity, biochemical composition, environmental tolerance, genetic stability, downstream recoverability, and safety.

A broader strain-discovery strategy should therefore move beyond identifying species with interesting metabolites toward systematic genotype-to-process-to-product evaluation. Such an approach could expand the biological foundation of diatom biotechnology while reducing dependence on a narrow group of model taxa.

7.7. Regulatory, Safety, and Market Translation

Regulatory uncertainty remains a major constraint for the commercialization of novel diatom-derived products. Requirements may differ according to whether the final product is intended as food, feed, a nutraceutical, cosmetic ingredient, biomaterial, or pharmaceutical. Consequently, evidence generated for one application cannot automatically be transferred to another. For food and feed applications, issues including contaminant accumulation, microbial safety, allergenicity, toxicological effects, and compositional consistency require systematic assessment [76]. These considerations are particularly important because the ability of diatoms to accumulate nutrients or environmental elements can be advantageous for some applications but undesirable where contaminants are present. Genetically modified or metabolically engineered strains introduce additional regulatory considerations concerning environmental release, containment, product safety, and traceability.

The absence of harmonized approaches for strain identity, biomass specifications, analytical characterization, safety evaluation, and labeling can increase uncertainty for both producers and regulators. Rather than relying solely on broad claims of regulatory harmonization, future development should prioritize application-specific safety dossiers, standardized analytical protocols, traceable production systems, and clearly defined quality specifications. Such measures would provide a more realistic pathway toward regulatory acceptance and market confidence.

7.8. Economic Viability and Integrated Biorefinery Strategies

Economic feasibility ultimately determines whether biological and technological advances can support sustained commercialization. The difficulty arises because biomass productivity, target-metabolite concentration, recovery efficiency, and product value are interdependent. A strain producing a high concentration of a valuable metabolite may nevertheless be economically unattractive if growth is slow, harvesting is difficult, or extraction requires substantial energy and purification.

Multi-product valorization is an important strategy for improving the resource efficiency and economic potential of diatom-based biorefineries. Rather than targeting a single product, integrated processing can recover multiple valuable fractions from the same biomass. For example, hydrothermal liquefaction of a diatom-dominated consortium has been investigated for the recovery of bio-crude and nanoscale biosilica, illustrating the potential for more comprehensive biomass utilization [77]. Such approaches can improve resource utilization and distribute cultivation and processing costs across several product streams. However, multiproduct recovery should not be assumed to guarantee economic viability. Additional separation steps may increase capital and operational requirements, while markets for individual fractions may differ substantially in scale and value. Consequently, biorefinery configurations require integrated techno-economic and life-cycle evaluation to determine whether the additional products genuinely improve process economics and environmental performance.

7.9. From Biological Potential to Industrial Readiness

Taken together, these bottlenecks demonstrate that the laboratory-to-market gap in diatom biotechnology is fundamentally a problem of integration and reproducibility. Biological productivity alone is insufficient when strain performance changes during scale-up, biochemical composition varies between batches, biomass recovery is costly, or regulatory requirements cannot be adequately addressed. Conversely, process optimization without

consideration of strain physiology or product quality may improve operational efficiency without producing a commercially relevant product.

A more effective translational framework should therefore connect five stages: strain selection and authentication → controlled cultivation and scale-up → standardized harvesting and downstream processing → product-specific quality and safety validation → techno-economic and regulatory assessment [78]. Feedback between these stages is essential because decisions at one level can strongly influence performance at another. For example, strain selection should consider downstream recoverability, while cultivation conditions should be designed around the compositional specifications required for the final product. Emerging approaches such as automated sensing, digital cultivation models, metabolic engineering, and data-driven process control may improve this integration, but their value will depend on validation under realistic cultivation conditions and across multiple production cycles [79,80]. Similarly, biorefinery strategies may enhance resource utilization where multiple product streams can be recovered efficiently, but their feasibility must be demonstrated through quantitative economic and environmental assessments.

Overall, the commercialization of diatom biotechnology will depend less on demonstrating that diatoms can produce valuable compounds and more on demonstrating that these compounds can be produced consistently, safely, and economically at relevant scale. Bridging this gap requires a shift from laboratory-centered optimization toward product-oriented, process-integrated development in which biological performance, cultivation robustness, downstream recovery, quality assurance, safety, economics, and regulatory requirements are evaluated together. Such integration represents a necessary step for converting the considerable biochemical diversity of diatoms into reliable contributions to sustainable food, feed, nutraceutical, and bio-based production systems.

8. Future Perspectives: From Nutritional Profiling to Predictive Diatom Biotechnology

Despite substantial progress in characterizing the nutritional and biochemical diversity of diatoms, important knowledge and translational gaps remain. Future research should move beyond descriptive profiling toward predictive, mechanistic, and application-oriented frameworks capable of linking strain characteristics and environmental responses with defined product outcomes. Such a transition will require closer integration of ecology, physiology, omics, cultivation engineering, and process-level validation. The integration of artificial intelligence (AI) and machine learning with diatom biotechnology offers an emerging route toward predictive optimization of biomass composition and production processes. AI-based approaches can integrate morphological, physiological, environmental, and biochemical datasets to identify complex relationships between cultivation conditions and diatom responses, supporting prediction, classification, and process optimization [81].

A first priority is to expand strain discovery beyond the relatively narrow group of established model organisms. Marine, freshwater, benthic, polar, and extremophilic diatoms represent a largely underexplored reservoir of physiological adaptations and biochemical diversity. Systematic comparative screening of these taxa could identify strains with desirable combinations of nutritional quality, environmental tolerance, biomass productivity, and metabolite profiles. However, future strain discovery should be coupled with standardized evaluation of growth performance, biochemical composition, genetic stability, safety, and downstream processing characteristics rather than focusing solely on the presence of individual compounds.

A second priority is to resolve the mechanisms underlying species- and strain-specific metabolic variability. Environmental factors such as nutrient availability, irradiance, temperature, salinity, and silica supply can substantially alter carbon allocation and the synthesis of proteins, lipids, pigments, carbohydrates, and other metabolites. Integrating genomics, transcriptomics, proteomics, metabolomics, and physiological measurements could help identify regulatory networks responsible for these responses and improve the ability to predict biochemical outcomes under defined cultivation conditions. Such mechanistic understanding may ultimately enable more precise selection and optimization of strains for specific nutritional or biotechnological applications.

Translation to industrial production represents another major research priority. Rather than relying predominantly on laboratory-scale optimization, future studies should incorporate pilot-scale validation, long-term cultivation experiments, process monitoring, downstream recovery, techno-economic assessment, and life-cycle evaluation at earlier stages of technology development. Particular attention should be given to maintaining compositional consistency and culture stability during scale-up. Product-specific quality specifications and validated analytical workflows will also be necessary to distinguish biologically interesting strains from those with genuine commercial potential. Integrated biorefinery approaches remain promising where multiple fractions can be efficiently recovered from a common biomass stream. The simultaneous valorization of proteins, omega-3 fatty acids, pigments, polysaccharides, biosilica, and other products could improve resource utilization and potentially distribute cultivation and processing costs across multiple value streams. However, future research should

quantitatively determine when multiproduct recovery improves rather than increases overall process complexity, using techno-economic and environmental assessments to identify application-specific configurations. Standardization and safety should develop alongside technological innovation [14,82]. Harmonized approaches for strain authentication, nutritional profiling, contaminant monitoring, product characterization, and safety evaluation would improve comparability among studies and facilitate regulatory assessment. Importantly, standardization should be product- and application-specific, because requirements for whole-cell feed biomass differ from those for purified nutraceutical or pharmaceutical ingredients.

Future applications of diatom biotechnology should increasingly consider the ecological context in which these organisms occur, integrating biological assemblages with physicochemical and environmental information to improve interpretation of freshwater ecosystem condition [83].

Finally, predictive cultivation and data-driven biotechnology provide an emerging opportunity to connect biological variability with process control. Sensor-based monitoring, mathematical modelling, machine-learning approaches, and digital process-control systems may improve prediction of biomass productivity and biochemical composition under changing environmental conditions. Their wider adoption, however, will require sufficiently large and standardized datasets, independent validation, and demonstrated performance under realistic cultivation conditions. Overall, the next phase of diatom biotechnology should shift from asking what compounds diatoms can produce toward determining which strains can produce defined products consistently, safely, sustainably, and economically under scalable conditions. This transition from descriptive nutritional profiling to predictive and product-oriented biotechnology represents an important pathway for realizing the broader potential of diatoms in food, feed, health, and circular bioeconomy applications.

9. Conclusions

Diatoms represent a promising resource for sustainable biotechnology because of their diverse biochemical composition and potential applications in aquaculture, nutraceuticals, functional foods and integrated biorefinery systems. Their protein, lipid, carbohydrate and pigment profiles vary considerably among taxa and are influenced by growth phase, nutrient availability, light, temperature and cultivation conditions. Although selected diatoms contain appreciable protein and valuable polyunsaturated fatty acids, including EPA, protein content alone does not establish protein quality, and the presence or nutritional significance of individual fatty acids must be supported by compound-specific evidence. Nutritional claims should therefore be based on validated compositional data rather than generalized assumptions about diatom biomass.

Climate resilience and bioeconomy development are important considerations for the future utilization of diatoms. Understanding how environmental stressors affect growth, biochemical composition and productivity is necessary to identify strains and cultivation conditions that maintain reliable biomass and product yields under changing environmental conditions. In parallel, integrating the production of high-value compounds with resource recovery and residual-biomass utilization may improve the resource efficiency of diatom-based biorefineries. However, these opportunities must be evaluated against cultivation requirements, harvesting and downstream processing costs, product safety, and environmental and economic performance.

Further progress requires standardized analytical methods for determining biochemical composition, improved comparability among species and cultivation studies, stronger evidence on nutritional quality and bioavailability, and validated food-safety assessments. The development of scalable production systems must also demonstrate reproducible yields, process stability and economic feasibility beyond laboratory-scale cultivation. Combining standardized biochemical characterization with climate-responsive cultivation strategies, life-cycle assessment and techno-economic analysis will help establish where diatom-based products can make a credible contribution to a sustainable and circular bioeconomy.

Author Contributions

S.S.: Writing original draft, formal analysis & visualization. H.P.: Reviewing, editing & visualization. A.T.: Reviewing & editing. J.V.: Conceptualization, supervision, reviewing & editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are not publicly available but are available from the corresponding author upon reasonable request.

Acknowledgments

The authors express their gratitude to the Illustrate platform for helping in creating the graphical illustrations.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

Generative AI was used solely for the creation of conceptual and illustrative figures in this manuscript. All AI-generated visual outputs were critically evaluated, modified where necessary, and verified by the authors for scientific accuracy and consistency with the cited literature. No AI-generated data, experimental results, references, or scientific interpretations were incorporated into the manuscript.

References

- Armbrust, E.V. The life of diatoms in the world's oceans. *Nature* **2009**, *459*, 185–192. <https://doi.org/10.1038/nature08057>.
- Falkowski, P.G.; Barber, R.T.; Smetacek, V. Biogeochemical Controls and Feedbacks on Ocean Primary Production. *Science* **1998**, *281*, 200–206. <https://doi.org/10.1126/science.281.5374.200>.
- Field, C.B.; Behrenfeld, M.J.; Randerson, J.T.; et al. Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components. *Science* **1998**, *281*, 237–240. <https://doi.org/10.1126/science.281.5374.237>.
- Pulz, O.; Gross, W. Valuable products from biotechnology of microalgae. *Appl. Microbiol. Biotechnol.* **2004**, *65*, 635–648. <https://doi.org/10.1007/s00253-004-1647-x>.
- Borowitzka, M.A. Biology of Microalgae. In *Microalgae in Health and Disease Prevention*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 23–72. <https://doi.org/10.1016/b978-0-12-811405-6.00003-7>.
- Roy, S.S.; Pal, R. Microalgae in Aquaculture: A Review with Special References to Nutritional Value and Fish Dietetics. *Proc. Zool. Soc.* **2015**, *68*, 1–8. <https://doi.org/10.1007/s12595-013-0089-9>.
- Guedes, A.C.; Amaro, H.M.; Malcata, F.X. Microalgae as sources of high added-value compounds—A brief review of recent work. *Biotechnol. Prog.* **2011**, *27*, 597–613. <https://doi.org/10.1002/btpr.575>.
- Nieri, P.; Carpi, S.; Esposito, R.; et al. Bioactive Molecules from Marine Diatoms and Their Value for the Nutraceutical Industry. *Nutrients* **2023**, *15*, 464. <https://doi.org/10.3390/nu15020464>.
- Patil, V.; Källqvist, T.; Olsen, E.; et al. Fatty acid composition of 12 microalgae for possible use in aquaculture feed. *Aquac. Int.* **2007**, *15*, 1–9. <https://doi.org/10.1007/s10499-006-9060-3>.
- Remize, M.; Brunel, Y.; Silva, J.L.; et al. Microalgae n-3 PUFAs Production and Use in Food and Feed Industries. *Mar. Drugs* **2021**, *19*, 113. <https://doi.org/10.3390/md19020113>.
- Calder, P.C. Marine omega-3 fatty acids and inflammatory processes: Effects, mechanisms and clinical relevance. *Biochim. Biophys. Acta Mol. Cell Biol. Lipids* **2015**, *1851*, 469–484. <https://doi.org/10.1016/j.bbalip.2014.08.010>.
- Steinrücken, P.; Mjøs, S.A.; Prestegard, S.K.; et al. Enhancing EPA Content in an Arctic Diatom: A Factorial Design Study to Evaluate Interactive Effects of Growth Factors. *Front. Plant Sci.* **2018**, *9*, 491. <https://doi.org/10.3389/fpls.2018.00491>.
- Safi, C.; Zebib, B.; Merah, O.; et al. Morphology, composition, production, processing and applications of *Chlorella vulgaris*: A review. *Renew. Sustain. Energy Rev.* **2014**, *35*, 265–278. <https://doi.org/10.1016/j.rser.2014.04.007>.
- Lu, X.; Yang, S.; He, Y.; et al. Nutritional Value and Productivity Potential of the Marine Microalgae *Nitzschia laevis*, *Phaeodactylum tricornutum* and *Isochrysis galbana*. *Mar. Drugs* **2024**, *22*, 386. <https://doi.org/10.3390/md22090386>.
- Chen, J.; Yang, J.; Du, H.; et al. Laminarin, a Major Polysaccharide in Stramenopiles. *Mar. Drugs* **2021**, *19*, 576. <https://doi.org/10.3390/md19100576>.

16. Mishra, A.; Medhi, K.; Malaviya, P.; et al. Omics approaches for microalgal applications: Prospects and challenges. *Bioresour. Technol.* **2019**, *291*, 121890. <https://doi.org/10.1016/j.biortech.2019.121890>.
17. Banskota, A.H.; Hui, J.P.M.; Blatt-Janmaat, K.; et al. Biochemical Characterization of Lipids, Proteins, and Polysaccharides from the Marine Diatom *Phaeodactylum tricornutum* Cultivated in Pilot-Scale Photobioreactors. *Molecules* **2026**, *31*, 1017. <https://doi.org/10.3390/molecules31061017>.
18. Reboloso-Fuentes, M.M.; Navarro-Pérez, A.; Ramos-Miras, J.J.; et al. Biomass nutrient profiles of the microalga *Phaeodactylum tricornutum*. *J. Food Biochem.* **2001**, *25*, 57–76. <https://doi.org/10.1111/j.1745-4514.2001.tb00724.x>.
19. Levitan, O.; Dinamarca, J.; Zelzion, E.; et al. Remodeling of intermediate metabolism in the diatom *Phaeodactylum tricornutum* under nitrogen stress. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 412–417. <https://doi.org/10.1073/pnas.1419818112>.
20. Courchesne, N.M.D.; Parisien, A.; Wang, B.; et al. Enhancement of lipid production using biochemical, genetic and transcription factor engineering approaches. *J. Biotechnol.* **2009**, *141*, 31–41. <https://doi.org/10.1016/j.jbiotec.2009.02.018>.
21. Brown, M.R.; Jeffrey, S.W.; Volkman, J.K.; et al. Nutritional properties of microalgae for mariculture. *Aquaculture* **1997**, *151*, 315–331. [https://doi.org/10.1016/s0044-8486\(96\)01501-3](https://doi.org/10.1016/s0044-8486(96)01501-3).
22. Wen, Z.Y.; Chen, F. Heterotrophic production of eicosapentaenoic acid by microalgae. *Biotechnol. Adv.* **2003**, *21*, 273–294. [https://doi.org/10.1016/s0734-9750\(03\)00051-x](https://doi.org/10.1016/s0734-9750(03)00051-x).
23. Hemaiswarya, S.; Raja, R.; Ravi Kumar, R.; et al. Microalgae: A sustainable feed source for aquaculture. *World J. Microbiol. Biotechnol.* **2011**, *27*, 1737–1746. <https://doi.org/10.1007/s11274-010-0632-z>.
24. Whyte, J.N.C. Biochemical composition and energy content of six species of phytoplankton used in mariculture of bivalves. *Aquaculture* **1987**, *60*, 231–241. [https://doi.org/10.1016/0044-8486\(87\)90290-0](https://doi.org/10.1016/0044-8486(87)90290-0).
25. Allen, A.E.; Dupont, C.L.; Oborník, M.; et al. Evolution and metabolic significance of the urea cycle in photosynthetic diatoms. *Nature* **2011**, *473*, 203–207. <https://doi.org/10.1038/nature10074>.
26. Onn, S.M.; Koh, G.J.; Yap, W.H.; et al. Recent advances in genetic engineering of microalgae: Bioengineering strategies, regulatory challenges and future perspectives. *J. Appl. Phycol.* **2025**, *37*, 247–264. <https://doi.org/10.1007/s10811-024-03367-y>.
27. Tyagi, R.; Singh, P.K.; Saxena, A.; et al. Exploring the nutraceutical potential of high-altitude freshwater diatom *Nitzschia* sp. in batch culture. *Syst. Microbiol. Biomanuf.* **2024**, *4*, 1262–1272. <https://doi.org/10.1007/s43393-024-00299-z>.
28. Bastos, C.R.V.; Maia, I.B.; Pereira, H.; et al. Optimisation of Biomass Production and Nutritional Value of Two Marine Diatoms (Bacillariophyceae), *Skeletonema costatum* and *Chaetoceros calcitrans*. *Biology* **2022**, *11*, 594. <https://doi.org/10.3390/biology11040594>.
29. Hernández-Sandoval, F.; Del Ángel-Rodríguez, J.; Núñez-Vázquez, E.; et al. Effects on Cell Growth, Lipid and Biochemical Composition of *Thalassiosira weissflogii* (Bacillariophyceae) Cultured under Two Nitrogen Sources. *Appl. Sci.* **2022**, *12*, 961. <https://doi.org/10.3390/app12030961>.
30. Brown, M.R.; Dunstan, G.A.; Norwood, S.J.; et al. Effects of harvest stage and light on the biochemical composition of the diatom *Thalassiosira pseudonana*. *J. Phycol.* **1996**, *32*, 64–73. <https://doi.org/10.1111/j.0022-3646.1996.00064.x>.
31. Vásquez Suárez, A.; Guevara, M.; González, M.; et al. Crecimiento y composición bioquímica de *Thalassiosira pseudonana* (Thalassiosirales: Thalassiosiraceae) bajo cultivo semi-continuo en diferentes medios y niveles de irradiancias. *Rev. Biol. Trop.* **2013**, *61*, 1003–1013. <https://doi.org/10.15517/rbt.v61i3.11776>.
32. Richmond, A.; Hu, Q. *Handbook of Microalgal Culture: Applied Phycology and Biotechnology*, 2nd ed.; Wiley-Blackwell: Oxford, UK, 2013. <https://doi.org/10.1002/9781118567166>.
33. Affan, A.; Karawita, R.; Jeon, Y.J.; et al. Growth characteristics and antioxidant properties of the benthic diatom *Navicula incerta* (Bacillariophyceae) from Jeju Island, Korea. *J. Phycol.* **2007**, *43*, 823–832. <https://doi.org/10.1111/j.1529-8817.2007.00367.x>.
34. Kang, K.H.; Qian, Z.J.; Ryu, B.; et al. Characterization of growth and protein contents from microalgae *Navicula incerta* with the investigation of antioxidant activity of enzymatic hydrolysates. *Food Sci. Biotechnol.* **2011**, *20*, 183–191. <https://doi.org/10.1007/s10068-011-0025-6>.
35. Coombs, J.; Darley, W.M.; Holm-Hansen, O.; et al. Studies on the Biochemistry and Fine Structure of Silica Shell Formation in Diatoms. Chemical Composition of *Navicula pelliculosa* during Silicon-Starvation Synchrony. *Plant Physiol.* **1967**, *42*, 1601–1606. <https://doi.org/10.1104/pp.42.11.1601>.
36. Pahl, S.L.; Lewis, D.M.; Chen, F.; et al. Growth dynamics and the proximate biochemical composition and fatty acid profile of the heterotrophically grown diatom *Cyclotella cryptica*. *J. Appl. Phycol.* **2010**, *22*, 165–171. <https://doi.org/10.1007/s10811-009-9436-7>.
37. Guillard, R.R.L.; Ryther, J.H. Studies of marine planktonic diatoms. I. *Cyclotella nana* Hustedt, and *Detonula confervacea* (Cleve) Gran. *Can. J. Microbiol.* **1962**, *8*, 229–239. <https://doi.org/10.1139/m62-029>.
38. Tiwari, A.; Saini, G.K.; Parikh, H.; et al. Diatom-Derived Biochemicals: An In-Depth Analysis of Polysaccharides, Extraction Methodologies, and Diverse Applications. *Appl. Biochem. Biotechnol.* **2026**, *198*, 1–28. <https://doi.org/10.1007/s12010-025-05414-x>.

39. Singh, P.K.; Bhattacharjya, R.; Lakshmi, N.J.; et al. Evaluation of the antioxidative response of diatoms grown on emerging steroidal contaminants. *Environ. Monit. Assess.* **2023**, *195*, 820. <https://doi.org/10.1007/s10661-023-11336-0>.
40. Imamoglu, E. Artificial Intelligence and/or Machine Learning Algorithms in Microalgae Bioprocesses. *Bioengineering* **2024**, *11*, 1143. <https://doi.org/10.3390/bioengineering11111143>.
41. Verma, J.; Mishra, M.; Rai, J.; et al. First Record of the Centric Diatom *Pleurosira laevis* (Ehrenberg) Compère, 1982 from the Ganga River at Prayagraj, India: Implications of Mass Gathering Events. *PhytoTalks* **2026**, *3*, 903–914. <https://doi.org/10.21276/pt.2026.v3.i2.9>.
42. Yaakob, M.A.; Mohamed, R.M.S.R.; Al-Gheethi, A.; et al. Influence of Nitrogen and Phosphorus on Microalgal Growth, Biomass, Lipid, and Fatty Acid Production: An Overview. *Cells* **2021**, *10*, 393. <https://doi.org/10.3390/cells10020393>.
43. Armin, G.; Inomura, K. Modeling the elemental stoichiometry and silicon accumulation in diatoms. *Curr. Res. Microb. Sci.* **2022**, *3*, 100164. <https://doi.org/10.1016/j.crmicr.2022.100164>.
44. Shang, X.; Li, X.; Sun, J. Transcriptomic insights into cell-cycle arrest and metabolic adaptation of *Skeletonema dohrnii* under silicon starvation. *Algal Res.* **2026**, *93*, 104452. <https://doi.org/10.1016/j.algal.2025.104452>.
45. Lapointe, A.; Kocademir, M.; Bergman, P.; et al. Characterization of polyphosphate dynamics in the widespread freshwater diatom *Achnanthes minutissimum* under varying phosphorus supplies. *J. Phycol.* **2024**, *60*, 624–638. <https://doi.org/10.1111/jpy.13423>.
46. Lovio-Fragoso, J.P.; de Jesús-Campos, D.; López-Eliás, J.A.; et al. Biochemical and Molecular Aspects of Phosphorus Limitation in Diatoms and Their Relationship with Biomolecule Accumulation. *Biology* **2021**, *10*, 565. <https://doi.org/10.3390/biology10070565>.
47. Gu, W.; Kavanagh, J.M.; McClure, D.D. A scalable model for EPA and fatty acid production by *Phaeodactylum tricornutum*. *Front. Bioeng. Biotechnol.* **2022**, *10*, 1011570. <https://doi.org/10.3389/fbioe.2022.1011570>.
48. Calderini, M.L.; Pääkkönen, S.; Salmi, P.; et al. Temperature, phosphorus and species composition will all influence phytoplankton production and content of polyunsaturated fatty acids. *J. Plankton Res.* **2023**, *45*, 625–635. <https://doi.org/10.1093/plankt/fbad026>.
49. Truong, T.Q.; Park, Y.J.; Koo, S.Y.; et al. Interdependence of fucoxanthin biosynthesis and fucoxanthin-chlorophyll a/c binding proteins in *Phaeodactylum tricornutum* under different light intensities. *J. Appl. Phycol.* **2023**, *35*, 25–42. <https://doi.org/10.1007/s10811-022-02856-2>.
50. Ebbing, T.; Kopp, L.; Frick, K.; et al. Exploring *Phaeodactylum tricornutum* for Nutraceuticals: Cultivation Techniques and Neurotoxin Risk Assessment. *Mar. Drugs* **2025**, *23*, 58. <https://doi.org/10.3390/md23020058>.
51. Bhattacharjya, R.; Marella, T.K.; Kumar, M.; et al. Diatom-assisted aquaculture: Paving the way towards sustainable economy. *Rev. Aquac.* **2024**, *16*, 491–507. <https://doi.org/10.1111/raq.12848>.
52. Martin-Jézéquel, V.; Hildebrand, M.; Brzezinski, M.A. Silicon metabolism in diatoms: Implications for growth. *J. Phycol.* **2000**, *36*, 821–840. <https://doi.org/10.1046/j.1529-8817.2000.00019.x>.
53. Spilling, K.; Seppälä, J.; Schwenk, D.; et al. Variation in the fatty acid profiles of two cold water diatoms grown under different temperature, light, and nutrient regimes. *J. Appl. Phycol.* **2021**, *33*, 1447–1455. <https://doi.org/10.1007/s10811-021-02380-9>.
54. Round, F.E.; Crawford, R.M.; Mann, D.G. *Diatoms: Biology and Morphology of the Genera*; Cambridge University Press: Cambridge, UK, 1990.
55. Pandey, L.K.; Bergey, E.A.; Lyu, J.; et al. The use of diatoms in ecotoxicology and bioassessment: Insights, advances and challenges. *Water Res.* **2017**, *118*, 39–58. <https://doi.org/10.1016/j.watres.2017.01.062>.
56. Sarker, N.K.; Kaparaju, P. Microalgal Bioeconomy: A Green Economy Approach Towards Achieving Sustainable Development Goals. *Sustainability* **2024**, *16*, 11218. <https://doi.org/10.3390/su162411218>.
57. Boyd, P.W.; Claustre, H.; Levy, M.; et al. Multi-faceted particle pumps drive carbon sequestration in the ocean. *Nature* **2019**, *568*, 327–335. <https://doi.org/10.1038/s41586-019-1098-2>.
58. Tréguer, P.; Bowler, C.; Moriceau, B.; et al. Influence of diatom diversity on the ocean biological carbon pump. *Nat. Geosci.* **2018**, *11*, 27–37. <https://doi.org/10.1038/s41561-017-0028-x>.
59. Syed, T.; Krujatz, F.; Iahadjadene, Y.; et al. A review on machine learning approaches for microalgae cultivation systems. *Comput. Biol. Med.* **2024**, *172*, 108248. <https://doi.org/10.1016/j.combiomed.2024.108248>.
60. Ding, W.; Ye, Y.; Yu, L.; et al. Physiochemical and molecular responses of the diatom *Phaeodactylum tricornutum* to illumination transitions. *Biotechnol. Biofuels Bioprod.* **2023**, *16*, 103. <https://doi.org/10.1186/s13068-023-02352-w>.
61. Butler, T.; Kapoore, R.V.; Vaidyanathan, S. *Phaeodactylum tricornutum*: A Diatom Cell Factory. *Trends Biotechnol.* **2020**, *38*, 606–622. <https://doi.org/10.1016/j.tibtech.2019.12.023>.
62. Smol, J.P.; Stoermer, E.F. *The Diatoms: Applications for the Environmental and Earth Sciences*, 2nd ed.; Cambridge University Press: Cambridge, UK, 2010.
63. Singhal, S.; Srivastava, P.; Verma, J. Diatom-Based Multifunctional Biogenic Nanostructures in Water Purification: From Mechanistic Understanding to Innovative Applications. *PhytoTalks* **2025**, *2*, 496–522. <https://doi.org/10.21276/pt.2025.v2.i3.8>.

64. Jeffryes, C.; Agathos, S.N.; Rorrer, G. Biogenic nanomaterials from photosynthetic microorganisms. *Curr. Opin. Biotechnol.* **2015**, *33*, 23–31. <https://doi.org/10.1016/j.copbio.2014.10.005>.
65. Uduman, N.; Qi, Y.; Danquah, M.K.; et al. Dewatering of microalgal cultures: A major bottleneck to algae-based fuels. *J. Renew. Sustain. Energy* **2010**, *2*, 012701. <https://doi.org/10.1063/1.3294480>.
66. Khan, M.I.; Shin, J.H.; Kim, J.D. The promising future of microalgae: Current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microb. Cell Fact.* **2018**, *17*, 36. <https://doi.org/10.1186/s12934-018-0879-x>.
67. Quinn, J.C.; Davis, R. The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling. *Bioresour. Technol.* **2015**, *184*, 444–452. <https://doi.org/10.1016/j.biortech.2014.10.075>.
68. Rawat, I.; Ranjith Kumar, R.; Mutanda, T.; et al. Dual role of microalgae: Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. *Appl. Energy* **2011**, *88*, 3411–3424. <https://doi.org/10.1016/j.apenergy.2010.11.025>.
69. Hixson, S.M.; Arts, M.T. Climate warming is predicted to reduce omega-3, long-chain, polyunsaturated fatty acid production in phytoplankton. *Glob. Change Biol.* **2016**, *22*, 2744–2755. <https://doi.org/10.1111/gcb.13295>.
70. Patwardhan, S.B.; Pandit, S.; Ghosh, D.; et al. A concise review on the cultivation of microalgal biofilms for biofuel feedstock production. *Biomass Convers. Biorefin.* **2024**, *14*, 7219–7236. <https://doi.org/10.1007/s13399-022-02783-9>. Correction in *Biomass Convers. Biorefin.* **2024**, *14*, 7237. <https://doi.org/10.1007/s13399-022-02881-8>.
71. Wang, J.; Zhang, B.; Huang, Y.; et al. Temperature-controlled microalgal biofilm detachment and harvesting assisted by ultrasonic from 3D porous substrates grafted with thermosensitive gels. *Environ. Res.* **2024**, *256*, 119245. <https://doi.org/10.1016/j.envres.2024.119245>.
72. Wang, J.; Liu, W.; Liu, T. Biofilm based attached cultivation technology for microalgal biorefineries—A review. *Bioresour. Technol.* **2017**, *244*, 1245–1253. <https://doi.org/10.1016/j.biortech.2017.05.136>.
73. Jebali, A.; Sanchez, M.R.; Hanschen, E.R.; et al. Trait drift in microalgae and applications for strain improvement. *Biotechnol. Adv.* **2022**, *60*, 108034. <https://doi.org/10.1016/j.biotechadv.2022.108034>.
74. Slade, R.; Bauen, A. Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. *Biomass Bioenergy* **2013**, *53*, 29–38. <https://doi.org/10.1016/j.biombioe.2012.12.019>.
75. Hu, Q.; Sommerfeld, M.; Jarvis, E.; et al. Microalgal triacylglycerols as feedstocks for biofuel production: Perspectives and advances. *Plant J.* **2008**, *54*, 621–639. <https://doi.org/10.1111/j.1365-313x.2008.03492.x>.
76. Jain, R.; Dhali, S.; Malik, A.; et al. Sustainable biorefining: Hydrothermal liquefaction of diatom biomass for bio-crude and nano-biosilica recovery. *Process Saf. Environ. Prot.* **2024**, *187*, 940–949. <https://doi.org/10.1016/j.psep.2024.05.025>.
77. Falcioratore, A.; Bowler, C. Revealing the molecular secrets of marine diatoms. *Annu. Rev. Plant Biol.* **2002**, *53*, 109–130. <https://doi.org/10.1146/annurev.arplant.53.091701.153921>.
78. Wali, Z.; Parikh, H.; Tyagi, R.; et al. Diatoms for sustainable aquaculture: Nutritional potential, cultivation strategies, and circular bioeconomy applications. *Phycol. J.* **2026**, *2*, 9. <https://doi.org/10.1186/s44377-026-00014-0>.
79. Al Saoud, H.A.; Sprynskyy, M.; Pashaei, R.; et al. Diatom Biosilica: Source, Physical-Chemical Characterization, Modification, and Application. *J. Sep. Sci.* **2022**, *45*, 3362–3376. <https://doi.org/10.1002/jssc.202100981>.
80. Adarchenko, I.; Kurbatova, A.; Porotnikova, N.; et al. Advanced Technologies for Bioeconomy: The Case of Microalgae Production. *Foresight STI Gov.* **2024**, *18*, 69–83. <https://doi.org/10.17323/2500-2597.2024.2.69.83>.
81. Singhal, S.; Srivastava, A.; Srivastava, P.; et al. Deciphering urban freshwater health through integrated assessment of benthic macroinvertebrate assemblage and physicochemical dynamics in artificial ponds of Prayagraj, India. *Discov. Ecol.* **2026**, *2*, 5. <https://doi.org/10.1007/s44396-025-00020-x>.
82. Parikh, H.; Dave, G.; Verma, J.; et al. Artificial intelligence in diatom science: Methods, progress and applications. *Aquat. Sci.* **2026**, *88*, 117. <https://doi.org/10.1007/s00027-026-01349-5>.
83. Srivastava, A.; Singhal, S.; Yadav, A.; et al. Harnessing RStudio Package for Ecological Insights: Monitoring Diatoms with DiaThor. *Comput. Ecol. Softw.* **2026**, *16*, 1–34.