

Sustainable Fucoxanthin Production from Diatoms via Green Phytohormones

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Abstract

This critical literature review evaluates sustainable strategies for fucoxanthin production from diatoms, addressing the bottleneck of relying on costly, synthetic phytohormones. The methodology comprises a comprehensive bibliographic search across academic databases, primarily Scopus, ScienceDirect, and Google Scholar, to synthesize recent peer-reviewed studies spanning from 2011 to 2026. By systematically comparing green phytohormone sourcing, this paper introduces a zero-waste biorefinery paradigm for scalable pigment biosynthesis. Quantitative synthesis reveals that phytohormone application drastically enhances pigment yields; notably, mixotrophic *Skeletonema costatum* treated with 3 mg/L indole-3-acetic acid (IAA) achieved fucoxanthin productivities of 442.11 µg/L/day, while *Phaeodactylum tricornutum* yielded 36.01 mg/L when elicited with 6-benzylaminopurine and 5-aminolevulinic acid. While wastewater provides a zero-cost nutrient stream, this analysis establishes that symbiotic microalgae-bacteria consortia offer a superior commercial approach. These engineered systems naturally supply essential elicitors like IAA in a controlled loop, bypassing contamination risks and intensive pretreatment costs. Ultimately, this review aims to identify the most economically viable and ecologically sustainable pathway for pharmaceutical-grade fucoxanthin production.

Keywords: *Fucoxanthin, Diatoms, Green Phytohormone, Symbiotic Diatom-Bacteria, Microalgae-Bacteria Consortia, Wastewater Valorization*

INTRODUCTION

The global demand for pharmaceuticals to combat diseases like Alzheimer's and obesity is continuously rising (Khaw et al., 2021; Sun et al., 2023). Consequently, fucoxanthin—a pigment abundant in brown macroalgae and diatoms—has emerged as a promising therapeutic candidate due to its potent anti-inflammatory, antioxidant, and anti-diabetic properties (Arora & Philippidis, 2020). Previous extraction efforts have primarily targeted macroalgae (Frazzini & Rossi, 2025). However, their minimal fucoxanthin concentrations (0.02–0.58 mg/g fresh weight) render commercial production impractical, driving the need for diatoms as a high-yield alternative (Khaw et al., 2021).

While existing reviews focus heavily on macroalgae, they lack a critical evaluation of scalable microalgal production. To overcome low baseline yields in microalgal cultivation, the application of phytohormones has proven highly effective in stimulating cell division and pigment biosynthesis (Lu & Xu, 2015). However, large-scale cultivation traditionally relies on purified, synthetic phytohormones, which are cost-prohibitive and generate chemical waste, contradicting sustainable biorefinery principles (Nur et al., 2026). To address this bottleneck, this review introduces a novel paradigm shift: utilizing "green phytohormones" as a sustainable sourcing strategy to replace costly and environmentally harmful synthetic elicitors. Specifically, this review

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evaluates upstream strategies and contrasts the valorization of phytohormone-rich organic wastewater with engineered microalgae-bacteria consortia. Ultimately, this analysis pioneers a highly controlled, closed-loop commercialization pathway, identifying symbiotic microbial alliances as the superior, zero-waste model for pharmaceutical-grade fucoxanthin production.

LITERATURE REVIEW

Commercial fucoxanthin production requires robust upstream optimizations, starting with precise strain selection (Gong et al., 2024; Wang et al., 2021). Marine diatoms like *Odontella aurita* and *Phaeodactylum tricornutum* are highly favored due to their massive pigment accumulation and lower contamination risks, with the latter classified as safe for human consumption in Europe (Turck et al., 2023; Wang et al., 2021). Conversely, freshwater strains like *Nitzschia palea* HY1 offer strategic advantages when utilizing agricultural or industrial wastewater as nutrient sources (Won et al., 2023).

Establishing baseline biomass requires fine-tuning growth medium compositions, particularly nitrogen, phosphorus, and silicate, which significantly influence fucoxanthin biosynthesis (Khaw et al., 2022; Nur et al., 2019). Beyond basic nutrients, diatoms demonstrate highly adaptable cultivation strategies dictated by light and carbon availability. Under photoautotrophic conditions, elevated CO₂ supplementation (1–5%) positively impacts both biomass and fucoxanthin yields, likely by serving as an essential carbon source or triggering an acid-induced stress response (McClure et al., 2018). However, peak accumulation remains highly strain dependent.

To push beyond autotrophic limits, mixotrophic cultivation leverages simultaneous light and organic carbon assimilation, yielding vastly superior productivity (Table 1). Supplementing media with glucose significantly enhances fucoxanthin and biomass in species like *Cyclotella cryptica* and *Nitzschia laevis* (Guo et al., 2016; Lu et al., 2018; Lu et al., 2019). Other organic substrates also prove highly synergistic. *P. tricornutum* thrives with tryptone or arginine and urea (Yang and Wei, 2020; Yang et al., 2022), while *Chaetoceros calcitrans* achieves exceptional fucoxanthin yields using glycerol and urea (Nur et al., 2024). Furthermore, utilizing glycerol in palm oil mill effluent (POME) for co-cultures (Nur, 2021), or combining indole-3-acetic acid (IAA), glycerol, CO₂, and specific LED spectra for *Skeletonema costatum*, dramatically amplifies pigment accumulation (Nur et al., 2026).

Conversely, heterotrophic cultivation relies entirely on organic carbon in the absence of light. Because fucoxanthin is a light-harvesting pigment requiring specific optimal irradiance (e.g., 10–100 $\mu\text{mol}/\text{m}^2/\text{s}$ for *P. tricornutum*), heterotrophy yields significantly lower pigment concentrations (Nur et al., 2019). Consequently, while heterotrophy is effective for maximizing cell growth, mixotrophy remains the most favorable strategy for optimizing commercial fucoxanthin accumulation (Lu et al., 2018; Nur et al., 2026).

RESEARCH METHODOLOGY

This study adopts a critical and systematic literature review methodology to evaluate the feasibility, mechanisms, and scalability of green phytohormone interventions for diatom-based fucoxanthin production.

Literature Search Strategy and Databases

This review follows narrative literature instead of bibliometric analysis. A comprehensive bibliographic search was conducted across major academic databases, primarily Scopus, ScienceDirect, and Google Scholar. The search covered publications primarily spanning 2011 to 2026 to prioritize recent advancements within the last 1–5 years, alongside foundational literature

on microalgal phytohormone interactions. The search strategy employed specific keyword combinations coupled with Boolean operators ('AND', 'OR', '*'): `("fucoxanthin" OR "carotenoid production")`

`AND ("diatom" OR "microalgae" OR "Phaeodactylum tricornutum" OR "Skeletonema costatum" OR "Chaetoceros" OR "Nitzschia")`

`AND ("phytohormone" OR "plant growth regulator" OR "auxin" OR "indole-3-acetic acid" OR "IAA" OR "cytokinin" OR "gibberellic acid")`

`AND ("green phytohormone" OR "wastewater valorization" OR "microalgae-bacteria consortia" OR "symbiosis" OR "circular biorefinery")`

Eligibility, Inclusion, and Exclusion Criteria

Articles retrieved from the initial database query were screened against defined criteria to ensure relevance, data integrity, and methodological rigor:

Inclusion Criteria:

- Peer-reviewed research articles and high-impact reviews detailing diatom/microalgal cultivation, trophic modes (photoautotrophic, mixotrophic, heterotrophic), and metabolic stimulation.
- Studies reporting quantitative bioprocess metrics, including biomass concentration (g/L or mg/L/d), fucoxanthin yield (mg/g or mg/L), and specific phytohormone dosage ranges.
- Articles evaluating sustainable sourcing pathways, such as organic/industrial wastewater valorization and synthetic microalgae-bacteria co-cultivation systems.

Exclusion Criteria:

- Non-peer-reviewed conference abstracts lacking comprehensive data sets, non-English publications, and patents without peer-reviewed verification.
- Studies focused exclusively on macroalgal harvesting without bioprocess relevance to microalgal scalability.
- Literature lacking clear experimental operating conditions or mechanistic interpretations of hormone-mediated pathways.

FINDINGS AND DISCUSSION

Phytohormones and their engineered structural analogs are vital signaling molecules that regulate microalgal metabolism at trace concentrations (Lu & Xu, 2015). Sourcing these regulators from sustainable alternatives, such as organic wastewater or symbiotic bacterial exudates, creates a zero-waste biorefinery model that drastically boosts biomass and high-value metabolites without excessive nutrient inputs (Kichouh-Aiadi et al., 2025).

The exogenous application of these molecules consistently maximizes diatom pigment production. In *Phaeodactylum tricornutum*, combinations like 6-benzylaminopurine (6-BAP) and 5-aminolevulinic acid (5-ALA) yielded 36.01 mg/L fucoxanthin (Lin et al., 2024), while gibberellic acid (GA3) and abscisic acid (ABA) increased dry biomass by 25% (Fierli et al., 2022). Similarly, salicylic acid and 6-BAP enhanced fucoxanthin by 43% in *Chrysochromulina rotalis* and 34% in *Entomoneis* sp., respectively (Kichouh-Aiadi et al., 2025), and phloroglucinol boosted fucoxanthin to 4.5 mg/g dry weight in *Thalassiosira pseudonana* (Liu et al., 2022).

Despite these successes, auxin application, particularly indole-3-acetic acid (IAA), reveals significant dosage and cultivation contradictions (Table 2). Under autotrophic conditions, a trace IAA dose (5 µg/L) optimally increased *P. tricornutum* carotenoids 2.48-fold (Chen et al., 2025).

Conversely, a massive 3 mg/L dose in mixotrophic *Skeletonema costatum* (with 200 mg/L glycerol and 3% CO₂) triggered an exceptional fucoxanthin productivity of 442.11 µg/L/day (Nur et al., 2026). Furthermore, modified auxin-like supermolecules (1 mg/L) have safely outperformed conventional IAA (5 mg/L) in boosting biomass (Wang et al., 2022). Thus, auxin toxicity limits and efficacy are highly variable, depending heavily on specific strains and trophic modes. The reliance on expensive synthetic hormones and toxic downstream extraction solvents contradicts green biorefinery principles and hinders commercial scalability (Nur et al., 2026). To resolve this critical bottleneck, future investigations must transition to green phytohormones, utilizing organic wastewater streams or harnessing symbiotic bacteria-microalgae consortia that naturally secrete essential elicitors like IAA and cytokinins.

Stability and Degradation Dynamics of Phytohormones in Cultivation Media

While exogenous phytohormones offer a massive opportunity to boost fucoxanthin, maintaining their stability in large-scale cultivation remains a critical hurdle. In intensive systems, these signaling molecules face constant stress from intense light, temperature shifts, and the microalgae's own metabolic breakdown (Table 3).

A hormone's lifespan largely depends on its origin. Natural auxins (e.g., IAA, IBA, PAA) are highly bioactive but structurally fragile, suffering rapid photodegradation under continuous lighting. Furthermore, microalgae actively assimilate and consume even stable natural elicitors like salicylic acid (SA). While this rapid uptake makes diatoms excellent candidates for wastewater bioremediation, it quickly depletes the stimulatory signal in production tanks (Kichouh-Aiadi et al., 2025). Overcompensating by dumping massive doses is not a viable workaround, as such overloads typically halt cell growth entirely.

To counter this rapid breakdown, the industry often relies on synthetic auxins (e.g., NAA, 2,4-D). However, their extreme stability is a double-edged sword: they resist degradation but easily accumulate to toxic levels and often require harsh organic solvents that harm the culture. Modern engineered alternatives effectively bridge this gap. For instance, auxin-like supermolecules—combining 4-aminobenzoic acid (pABA) with diethylethanolamine (DEEA)—deliver exceptional water solubility and thermal stability. This ensures a safe, continuous metabolic push without the toxicity risks of traditional synthetics.

Phytohormones do not act in a vacuum; they are simply biochemical switches. To physically assemble fucoxanthin, the cell requires adequate raw materials and energy. Therefore, the true potential of phytohormones is unlocked only through synergistic cultivation parameters. For example, their impact is vastly magnified under mixotrophic conditions. When supplied with abundant organic carbon (like glycerol) and inorganic carbon (CO₂), the cells secure the structural backbone necessary for massive pigment synthesis. Paired with specific light spectra, such as broad-spectrum white LEDs to fuel ATP/NADPH production, this integrated strategy provides the precise energy and materials needed to execute the hormone-induced metabolic shifts.

Green Phytohormone Alternatives and Scalability

Relying on purified, synthetic phytohormones creates a major economic and environmental bottleneck for large-scale microalgal cultivation. While effective, their high costs and chemical waste directly contradict circular biorefinery principles. To remain competitive, the industry must pivot to "green phytohormones"—sourcing growth promoters from organic waste, biological interactions, or low-cost bio-based analogs rather than synthetic labs to drastically cut operational costs and environmental impact (Table 4).

Integrating microalgae cultivation with industrial or pharmaceutical wastewater offers a highly promising, zero-cost nutrient stream. For instance, industrial effluents frequently contain 15

to 500 mg/L of salicylic acid (SA), a potent phytohormone (Kichouh-Aiadi et al., 2025). Microalgae actively assimilate these effluent-derived hormones to fuel their own growth while concurrently purifying the water, creating a synergistic bioremediation model. Furthermore, engineering stable, low-cost "supermolecules" from abundant natural plant metabolites, like 4-aminobenzoic acid (pABA), safely mimics hormone activity without the toxicity of traditional synthetics (Wang et al., 2022).

However, managing the complex, fluctuating nature of organic waste streams remains a critical challenge. Unpredictable levels of heavy metals, antibiotics, or competing microorganisms in wastewater can easily stunt algal growth or contaminate pharmaceutical-grade products. Resolving this requires developing standardized pretreatment methods or engineering robust microalgal consortia capable of maintaining stable fucoxanthin yields in outdoor, commercial-scale systems (Nur et al., 2026).

Challenges and Opportunities

Commercializing microalgal fucoxanthin faces steep bottlenecks, including rigid cell walls that complicate extraction, high cultivation costs, and the geographic constraints of relying on marine species like *Phaeodactylum tricornutum* (Foo et al., 2021). Thus, finding easily harvestable freshwater diatoms and navigating complex pharmaceutical regulations remain major hurdles.

Despite these challenges, microalgae thrive in controlled systems and seamlessly integrate with wastewater treatment. Effluents like municipal waste, palm oil mill effluent (POME), mariculture runoff, and dairy wastewater provide complex, zero-cost phytohormones. (Table 5) For instance, native bacteria in raw POME synthesize IAA to stimulate *Chlorella* (Zalfiatri et al., 2020), while mariculture wastewater naturally supplies cytokinins and gibberellins. In marine diatoms like *Chaetoceros* and *Nitzschia*, these hormones mitigate oxidative stress; remarkably, faded photosynthetic pigments in these environments often indicate a hormone-mediated metabolic shift toward high intracellular lipid and pigment accumulation, rather than cell death (Liu et al., 2024).

This approach scales across distinct biological profiles. *Spirulina*, whose cell size generally exceeds 30 microns, requires immense energy to maintain its structural integrity. Cultivating it in heavy, organic dairy wastewater provides the necessary substrates and endogenous hormones to synthesize proteins without the extreme energetic toll of strict photoautotrophy (Álvarez-Montero et al., 2025). Matching such physiological traits with specific effluent profiles—like the IAA and abscisic acid found in sugarcane vinasse—successfully bypasses the need for expensive synthetic media (Zamarreño et al., 2022).

As illustrated in Figure 1, combining green phytohormones with industrial CO₂ capture transforms production into a circular biorefinery, enabling the lucrative co-production of omega-3 fatty acids and proteins (Pocha et al., 2022). Coupling this framework with advancements in genetic and metabolic engineering will firmly establish microalgae as a premier pharmaceutical source (Grama et al., 2022; Gupta et al., 2025).

Ultimately, engineered microalgae-bacteria consortia represent the most transformative and intrinsically sustainable frontier (Figure 2). While wastewater valorization is compelling, it introduces unpredictable contaminants and pretreatment costs. In contrast, mutualistic consortia establish a fully controlled, closed-loop biological system. Bacteria naturally secrete powerful exogenous elicitors, notably IAA, to significantly enhance algal biomass and pigment biosynthesis (González-González & De-Bashan, 2021; Zhang et al., 2022). Concurrently, photosynthetic diatoms exude carbon-rich extracellular polymeric substances (EPS) to sustain their bacterial partners (Perera et al., 2021). Scaling these robust microbial alliances to commercial photobioreactors maximizes high-value marine therapeutics while drastically minimizing external chemical inputs

(Wang et al., 2024).

CONCLUSION AND FURTHER RESEARCH

While this review establishes a comprehensive conceptual framework for green phytohormone interventions, several limitations must be acknowledged. First, the findings synthesized in this study rely predominantly on published laboratory-scale data, which inherently restricts the immediate predictability of commercial-scale outcomes. As highlighted by Wang et al. (2021) and Foo et al. (2021), the transition from highly controlled laboratory photobioreactors to commercial-scale cultivation introduces complex abiotic and biotic variables that are often not fully captured in bench-scale models.

Second, although wastewater valorization provides a zero-cost phytohormone source, its highly variable composition poses a significant technological barrier. The unpredictable presence of competing microorganisms, heavy metals, or secondary contaminants in effluents makes it difficult to guarantee the stable, pharmaceutical-grade fucoxanthin yields required by the industry, an issue emphasized by the complex effluent profiles described by Gu et al. (2025).

Furthermore, while engineered microalgae-bacteria consortia are proposed as a superior closed-loop alternative, maintaining the population stability of these mutualistic relationships during prolonged, continuous cultivation cycles remains challenging. Evidence from Dao et al. (2018) and González-González & De-Bashan (2021) indicates that microbial dynamics can fluctuate under operational stress, meaning the proposed framework requires extensive empirical verification before industrial deployment.

To address these boundaries, future research must prioritize the experimental validation of green phytohormone strategies—particularly symbiotic consortia—in pilot-scale systems. Future investigations should also focus on integrating these biological frameworks with advanced genetic engineering techniques, as suggested by Grama et al. (2022) and Gupta et al. (2025), to construct robust, scalable biorefineries that can consistently meet the stringent safety and quality regulations for novel foods and pharmaceuticals outlined by Turck et al. (2023).

This review advances future research in sustainable biorefinery systems by establishing a clear framework for transitioning from synthetic to biologically sourced phytohormones. The practical implication is a scalable, zero-waste production model for pharmaceutical-grade fucoxanthin. However, this study is limited by its reliance on published literature and the current lack of extensive commercial-scale experimental validation for the proposed consortia framework. Future research must prioritize empirical verification of these symbiotic systems in pilot-scale photobioreactors to confirm their industrial viability and provide concrete recommendations for commercial deployment.

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FIGURES AND TABLES

Table 1. Production of fucoxanthin from microalgae under mixotrophic cultivation condition

Microalgae Species	Organic Carbon Substrate	Biomass Production	Fucoxanthin	Medium	Remarks	References
<i>Cyclotella cryptica</i>	Glucose	584 mg/L	3.38 mg/L/d	F/2	-	(Guo et al., 2016)
<i>Phaeodactylum tricornutum</i>	Tryptone	6.52 g/L	8.22 mg/L/d	F/2	Two stage cultivation using LED	(Yang and Wei, 2020)
<i>Nitzschia laevis</i>	Glucose	1.91 g/L	5.42 mg/L/d	LDM	-	(Lu et al., 2018)
<i>C. calcitrans</i>	Glycerol	147.72 mg/L/d	3.2 mg/L/d	F/2	Two stage cultivation using LED + urea as nitrogen	(Nur et al., 2024)
<i>Phaeodactylum tricornutum</i>	Arginine	3.18 g/L	2.68 mg/L/day	F/2	Urea as nitrogen source	(Yang et al., 2022)
<i>Nitzschia laevis</i>	Glucose	2.34 g/L	36.5 mg/L	LDM	fucoxanthin and EPA contents are linear	(Lu et al., 2019)
<i>Co culture of Nannochloropsis sp. and Thalassiosira sp.</i>	Glycerol	299 mg/L/d	5.59 mg/L	Palm oil mill effluent + F/2	-	(Nur, 2021)
<i>Skeletonema costatum</i>	Glycerol, IAA	35.84 mg/L/d	442.11 µg L ⁻¹ day ⁻¹	F2	Additional LED and 3% CO ₂	(Nur et al., 2026)

Table 2. Summary of Phytohormone/Auxin Effects on Microalgal Growth Condition and Pigment Production

Microalgae Species	Phytohormone / Elicitor & Optimum Dose	Operating Conditions	Fucoxanthin Yield / Content	Biomass / Growth Rate	Reference
<i>Skeletonema costatum</i>	Indole-3-acetic acid (IAA), 3 mg/L	Mixotrophic (glycerol 200 mg/L), 3% CO ₂ , white LED, 12:12 L/D, 28°C	442.11 µg/L/d (Content: 0.10%)	Yield: 35.84 mg/L/d (GR: 0.174 d ⁻¹)	Nur et al., 2026
<i>Phaeodactylum tricornutum</i>	Gibberellic acid (GA3) + Absciscic acid (ABA), 2 mg/L each	Batch culture, white light (65 µmol m ⁻² s ⁻¹), 14:10 L/D, 20°C	Yield up to 1.3 mg/L	Dry biomass yield increased by 25%	Fierli et al., 2023
<i>Phaeodactylum tricornutum</i>	6-benzylaminopurine (6-BAP) + 5-aminolevulinic acid (5-ALA), 1.0 mg/L each	f/2 medium, white light (101.75 µmol m ⁻² s ⁻¹), 16:8 L/D, 23°C	36.01 mg/L (Content: 24.01 mg/g)	1.50 g/L (Productivity : 0.15 g/L/d)	Lin et al., 2024

Microalgae Species	Phytohormone / Elicitor & Optimum Dose	Operating Conditions	Fucoxanthin Yield / Content	Biomass / Growth Rate	Reference
<i>Phaeodactylum tricornutum</i>	IAA, 5 µg/L	f/2 medium, white fluorescent (90 µmol m ⁻² s ⁻¹), 12:12 L/D, 20°C	<i>Not isolated</i> (Total Carotenoids increased 2.48-fold at 96 h)	Cell density growth promotion rate of 10.6%	Chen et al., 2025
<i>Phaeodactylum tricornutum</i>	Auxin-like supermolecule (SM), 1 ppm & IAA, 5 ppm	f/2 medium, 2000 lx, 12:12 L/D, 25°C	<i>Not determined</i> (Focused on EPA; EPA reached 31.77%)	Biomass increased by 23.72% (0.72 g/L)	Wang et al., 2022
<i>Thalassiosira pseudonana</i>	Phloroglucinol, 100 µM	f/2 medium, cool light fluorescence (50 µE m ⁻² s ⁻¹), 16:8 L/D, 18°C	~4.5 mg/g DW	Dry cell weight ~60 mg/L	Liu et al., 2022
<i>Chrysochromulina rotalis</i>	Salicylic acid (SA), 30 mg/L	f/2 medium, RGBW LEDs (135 µmol m ⁻² s ⁻¹), 12:12 L/D, 21°C	Increased by 43%	Highest overall performance (GRG: 0.905)	Kichouh-Aiadi et al., 2025

Microalgae Species	Phytohormone / Elicitor & Optimum Dose	Operating Conditions	Fucoxanthin Yield / Content	Biomass / Growth Rate	Reference
<i>Heterosigma akashiwo</i>	Gibberellic acid (GA), 30 mg/L	f/2 medium, RGBW LEDs (135 $\mu\text{mol m}^{-2} \text{s}^{-1}$), 12:12 L/D, 21°C	Increased by 27%	Enhanced overall performance (GRG: 0.770)	Kichouh-Aiadi et al., 2025
<i>Entomoneis</i> sp.	6-benzylaminopurine (6BAP), 15 mg/L	f/2 medium, RGBW LEDs (135 $\mu\text{mol m}^{-2} \text{s}^{-1}$), 12:12 L/D, 21°C	Increased by 34%	Enhanced overall performance (GRG: 0.814)	Kichouh-Aiadi et al., 2025

Table 3. Stability, solubility, and degradation dynamics of natural and synthetic phytohormones in microalgal cultivation

Phytohormone Category	Specific Compounds	Stability and Solubility Characteristics	Degradation and Efficacy-Limiting Factors	Reference
Natural Auxins	Indole-3-acetic acid (IAA), Indole-3-butyric acid (IBA), Phenylacetic acid (PAA), 4-chloroindole-3-acetic acid (4-Cl-IAA)	Limited water solubility; typically requires organic solvents (e.g., ethanol) for initial stock preparation.	Highly susceptible to rapid photodegradation under cultivation lights and enzymatic breakdown by microalgae. High doses can trigger secondary inhibitory compounds (e.g.,	Nur et al., 2026 ; Wang et al., 2022

Phytohormone Category	Specific Compounds	Stability and Solubility Characteristics	Degradation and Efficacy-Limiting Factors	Reference
			ethylene).	
Other Natural Hormones	Salicylic Acid (SA), 6-benzylaminopurine (6-BAP), 5-aminolevulinic acid (5-ALA)	Moderate to high stability in complex aquatic environments; 6-BAP and 5-ALA can dissolve in water without harsh solvents.	Biological degradation; microalgae actively assimilate and biodegrade these compounds over time in batch cultures, requiring precise redosing to maintain the metabolic signal.	Kichouh-Aiadi et al., 2025 ; Lin et al., 2024
Synthetic Auxins	Naphthalene acetic acid (NAA), 2,4-Dichlorophenoxyacetic acid (2,4-D)	Chemically stable and highly persistent in aquatic environments compared to their natural counterparts.	Resist biological breakdown, meaning they persist in the media long-term. However, they can easily accumulate to toxic levels and cause severe cell cycle arrest if misdosed.	Hunt et al., 2011 ; Piotrowska-Niczyporuk & Bajguz, 2014 ; Hosseini Madani et al., 2020
Engineered Hormones	Auxin-like Supermolecule (SM: pABA-DEEA)	Excellent water solubility due to hydrogen bond formation and robust thermal stability.	Resists rapid physicochemical degradation and entirely bypasses the need for toxic organic solvents, ensuring a prolonged, safe lifespan in the	(Wang et al., 2022)

Phytohormone Category	Specific Compounds	Stability and Solubility Characteristics	Degradation and Efficacy-Limiting Factors	Reference
			culture.	

Table 4. Comparison of Traditional vs. Green Phytohormone Sourcing Strategies

Sourcing Strategy	Examples	Advantages for Scalability	Current Challenges / Disadvantages	Reference
Traditional Synthetic Sourcing	Purified IAA, Synthetic Zeatin, 2,4-D	Precise dosing; highly predictable metabolic responses in controlled laboratory settings.	Extremely expensive for large-scale photobioreactors; manufacturing processes are not environmentally sustainable.	(Nur et al., 2026)
Industrial & Pharmaceutical Wastewater	Salicylic Acid (SA) found in effluents (15–500 mg/L)	Provides a free, continuous supply of hormones; enables simultaneous wastewater bioremediation and biomass production.	Effluents can have fluctuating compositions and may contain toxic heavy metals or competing bacteria that inhibit growth.	(Gu et al., 2025)
Engineered Bio-based Analogs	Auxin-like supermolecules (e.g., combining natural pABA and DEEA)	Utilizes cheap, naturally occurring plant metabolites (pABA) to create highly stable, water-soluble, and low-cost growth promoters.	Still requires chemical synthesis and formulation, though it is much greener and cheaper than traditional synthetic auxins.	(Wang et al., 2022)

Sourcing Strategy	Examples	Advantages for Scalability	Current Challenges / Disadvantages	Reference
Microbial Symbiosis (Co-cultivation)	Bacteria naturally secreting IAA or cytokinins	Creates a self-sustaining ecosystem; zero need for external chemical dosing; lowers overall nutrient costs.	Difficult to maintain stable symbiotic populations in open outdoor ponds; bacterial overgrowth can crash the microalgal culture.	(Dao et al., 2018)

Table 5. Green phytohormone from wastewater

Phytohormone Type	Wastewater Source	Microorganism(s) Cultivated	References
Auxin (Indole-3-acetic acid / IAA)	Municipal / Urban Wastewater	<i>Scenedesmus</i> sp., <i>Chlorella vulgaris</i> , <i>Synechocystis</i> sp.	(Álvarez-González et al., 2023)
Cytokinins (e.g., Zeatin), Gibberellins (GA3)	Mariculture / Aquaculture Wastewater	<i>Oocystis borgei</i> , <i>Chaetoceros</i> sp., <i>Nitzschia</i> sp.	(Liu et al., 2024)
Auxins (IAA), Gibberellins	Dairy & Livestock Wastewater	<i>Scenedesmus</i> sp., <i>Spirulina</i> (<i>Arthrospira platensis</i>)	(Álvarez-Montero et al., 2025)
Auxin (IAA), Absciscic Acid (ABA)	Sugarcane Vinasse	<i>Chlorella vulgaris</i> , <i>Desmodesmus</i> sp., <i>Euglena</i> sp.	(Zamarreño et al., 2022)
Auxin (IAA)	Palm Oil Mill Effluent (POME)	<i>Chlorella</i> sp. (often cultivated in symbiosis with native bacteria like <i>Azospirillum</i> sp.)	(Zalfiatri et al., 2020)

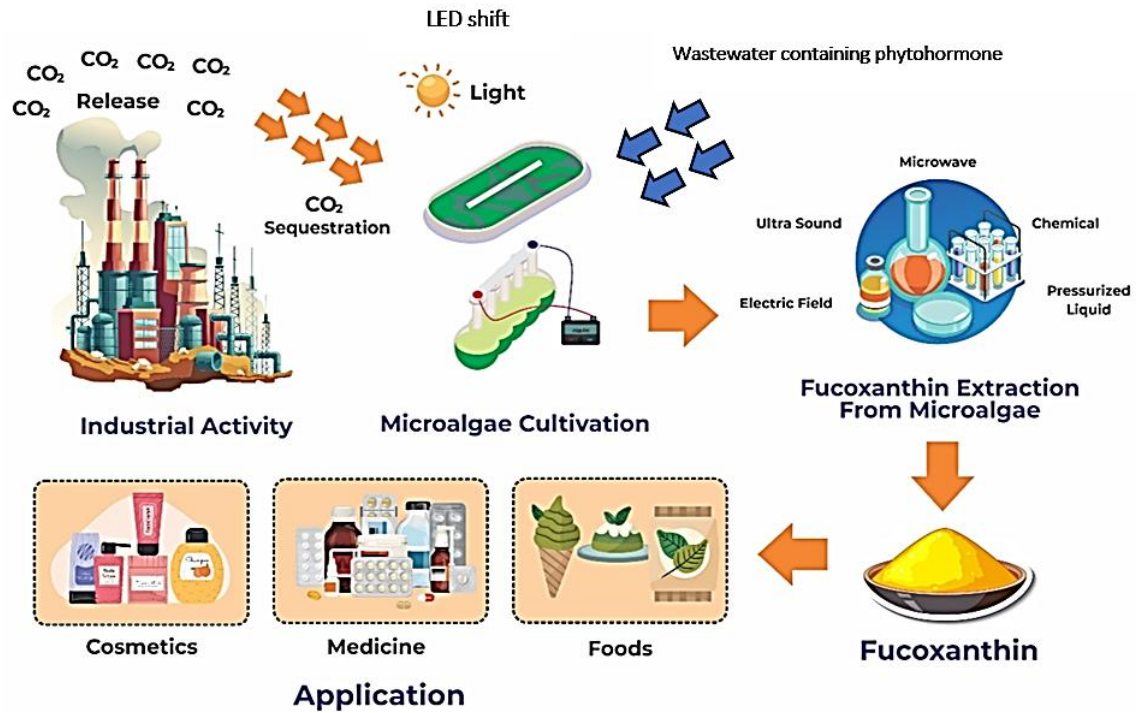


Figure 1. Integrated concept of microalgae cultivation and CO₂ sequestration producing fucoxanthin and other valuable compounds

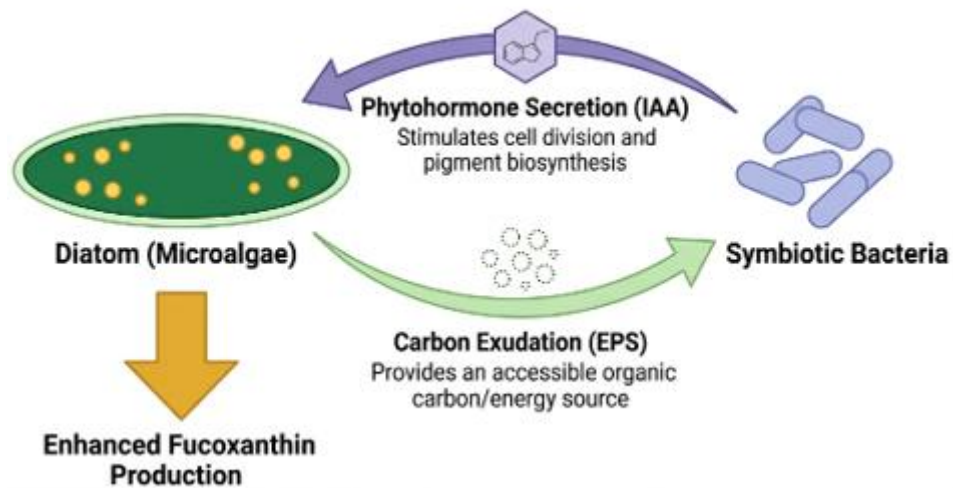


Figure 2. Schematic model of the symbiotic interaction between a Diatom (Microalgae) and bacteria