Exploring the Role of Carbon-Based Nanomaterials in Microalgae for the Sustainable Production of Bioactive Compounds and Beyond

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ABSTRACT: An enchanting yet challenging task is the development of higher productivity in plants to meet the ample food demands for the growing global population while harmonizing the ecosystem using front-line technologies. This has kindled the practice of green microalgae cultivation as a driver of key biostimulant products, targeting agronomic needs. To this end, a prodigious and economical strategy for producing bioactive compounds (sources of secondary metabolites) from microalgae using carbon-based nanomaterials (CNMs) as a platform can circumvent these hurdles. Recently, the nanobionics approach of incorporating CNMs with living systems has emerged as a promising technique to develop organelles with new and augmented functions. Herein, we discuss the importance of 2D carbon nanosheets (CNS) as an alternative carbon source for the phototrophic cultivation of microalgae. CNS not only aids in cost reduction for algal cultivation but also confers combinatorial innate or exogenous functions that enhance its programmed biosynthetic metabolism, proliferation, or tolerance to stress. Moreover, the inherent ability of CNS to act as efficient biocatalysts can enhance the rate of photosynthesis. The primary focus of this mini-review is the development of an economic route for enhanced yield of bioactive compounds while simultaneously serving as a heterogeneous platform for enhancing the sustainable production of biostimulants including bioactive compounds from algal biomass for pharmaceutical and nutraceutical applications.

INTRODUCTION

With the food-energy nexus, in the current scenario, the most formidable challenge of an agroecosystem is to feed the expanding world population, wherein microalgae are of vital and pragmatic importance in the production of various biostimulant products including high-value-added bioactive compounds. Additionally, to overcome the exigencies of rapidly exhausting fossil fuels, a new frontier lying at the interface of nanotechnology and algal biology could revitalize the amplified functions along with beneficial abilities to the microalgae as the cherry on the cake. Microalgae have been used as a food source for over 1500 years, as they are a rich source of bioactive metabolites and are a popular choice for the pharmaceutical industry, especially in drug development. Algal species have evolved as a complete oxygenic photosynthetic system acting as the epicenter in the genesis of accelerated multifunctional metabolomics and governing the negative carbon footprint. Microalgae are the best potential source of biofuels as alternatives to fossil fuels. Microalgae are capable of accumulating a high lipid content, usually representing 20–50% of the total biomass in dry weight (DW). However, the lipid content may vary species to species. The main components of microalgae are fatty acids, wax esters, sterols, hydrocarbons, ketones, and pigments such as carotenoids, chlorophylls, and phycobilins. Interestingly, advances in the design and processing of CNMs can produce the molecular machinery to boost the photosynthetic processes and tailor the physicochemical functions of organelles within the algal biosystem, thus allowing the microalgae species to serve as a valuable source for the sustainable production of high-value-added bioactive components. Herein, the exceptional light-harvesting ability of CNMs make them a key model for the development of artificial photosynthesis. The incorporation of easily manufactured CNMs to the adaptive algal cell framework enables combinatorial innate or exogenous functions that augment its biosynthetic pathways, programmed metabolism, proliferation, conductivity, or tolerance to stress. Moreover, they have the potential to absorb sunlight and couple to the photosynthetic system to produce a staggering biomass. Most algal extracts contain carbohydrates, proteins, minerals, oils, fats, and polyunsaturated fatty acids as well as bioactive

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compounds which possess antioxidant, antibacterial, antifungal, antiviral, antitumor, and anti-inflammatory properties. The introduction of CNMs to the algal system establishes a sustainable alternate route for the extraction of various bioactive components advancing pivotal roles in prevention and treatment of human health diseases such as cardiovascular, cancer, inflammation, and numerous nervous system disorders. These bioactive compounds are essential nutrients that modulate several metabolic processes and promote human health. In contrast to other synthetic drugs, algal drugs are naturally endowed with numerous promising attributes, such as being biocompatible, biodegradable, and nontoxic in nature, which establish algae as an exceptional source for extraction of bioactive compounds.

Recent attempts have used genetic engineering to enable the creation of recombinant proteins, as well as optogenetic control to induce gene expression. Plants became a biotechnological focus in the late 1980s as an expression system for recombinant proteins, because they offer all of the benefits of higher eukaryotic expression systems but are powered by photosynthesis and thus do not require external carbon sources. Similarly, chemical stresses, physiological stresses, transcription factor engineering, genetic engineering, and light-filtering devices are some of the methods used to improve microalgae growth and bioactive component accumulation. However, research on algal growth with nanomaterials is widely reported, whereas their scope in genetically modified strains for recombinant protein expression is rare, calling for further investigations in this highly promising field.

There are three different modes of cultivation for microalgae such as photoautotrophic, heterotrophic, and mixotrophic. Generally, the photoautotrophically grown algal cells become denser, and growth becomes restricted to the availability of light due to the phenomenon of self-shading, caused by the neighboring microalgal cells. However, heterotrophic and mixotrophic cultures resort to organic carbon sources to counter the limitations observed in the case of photoautotrophic cultivation. Nevertheless, these modes of cultivation increase the costs of maintenance along with offering a favorable environment for the growth of unwanted microorganisms. This would result in algal culture contamination, thereby hampering the algal growth. Subsequently, these disadvantages affect the economic capability and sustainability of algal biomass for the mass production of bioactive compounds. Henceforth, there is a vital need for development of an economically viable and environmentally sustainable route for the enhanced production of bioactive compounds. Concurrently, this proposal also tries to pinpoint the future roadblocks to realizing the full advantage of microalgae-based bioproducts.

CNMs are a developing area of nanomaterials that deals with a promising approach in drug delivery, tissue engineering, medical transplants, and other applications. CNMs are defined as materials with sizes ranging from 1 to 100 nm. CNMs hold exceptional properties that can be modified through the synthesis process to augment their characteristics such as surface area, optical property, multifunctional surface morphology, drug delivery, biocompatibility, and immunogenicity. There are numerous types of CNMs such as nanocarbon, fullerene, nanodiamond, graphene nanosheets, graphene oxide, single walled carbon nanotubes (SWCNTs), carbon nanotubes multiwalled (MWCNTs), graphene quantum dots (GQDs), and carbon foam. CNMs have unique characteristics that can be applied to various biological applications. Moreover, nitrogen doping in CNMs can help to establish a highly porous architecture, improved catalytic activity, and biocompatibility. Additionally, these properties promote the adherence of CNMs to the cellular surfaces, augmenting the yield of metabolic products. These improved CNMs exhibit various inherent properties and are extensively used.

CNMs can be classified as 0D-CNMs (i.e., fullerene, diamonds, and carbon dots), 1D-CNMs (i.e., carbon nanofibers (CNFs), CNTs, and diamond nanorods), 2D-CNMs (i.e., graphene, carbon nanosheets (CNs), and graphite sheets), and 3D-CNMs. Therefore, we concluded a review of CNMs, highlighting 2D CNMs such as CNS and their role in algal biotechnology for the sustainable production of bioactive compounds and beyond. Table 1 shows various types of CNMs and their commercial applications.

### ROLE OF CNMS IN ENERGY AND ENVIRONMENTAL SECTOR APPLICATIONS

Next-generation “super functional materials” with increased novel capabilities are needed to fulfill rising energy demand, mitigate food shortages, and solve global environmental pollution at the vital energy—food—environment nexus. The present nonrenewable energy resources will not be able to supply the ever-increasing energy demand. As a result, renewable energy resources are in huge demand and are better for the environment. The existing method of producing energy and fuels from petroleum is unsustainable. Microalgae feedstocks and processes must therefore be improved for commercial and economic potential, high output, sustainability, and environmental friendliness. Compound recovery, energy consumption, selectivity, and scalability are other issues.

| sample number | CNMs                  | synthesis method                                      | novelty                                                                 | applications                          | refs       |
|---------------|-----------------------|------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------|------------|
| 1             | graphene              | chemical vapor deposition (CVD), mechanical exfoliation, and laboratory production | flammable, most reactive form of carbon electronic conductivity, lubricity, and anisotropy | bioimaging, biosensing, bone implantation, and drug delivery | 25,26      |
| 2             | graphite              | industrial and laboratory synthesis, naturally obtained | high strength, electronic properties                                   | lubricants, electrode components, and mechanical heart valves | 27         |
| 3             | carbon nanotubes      | CVD and large-scale production in laboratory          | high strength, insoluble in water, stable structure                     | biosensors, nanocomposite materials as scaffolds for tissue engineering | 28,29      |
| 4             | fullerenes            | large scale synthesis in laboratory and CVD           | high strength, high thermal conductivity                                | pharmaceutical industry, beneficial in IT devices and diagnostic purposes | 30         |
| 5             | carbon nanofibers     | CVD, laboratory production, and templating            | nonvolatile substance and hard                                         | cancer therapy, biosensing, and wound dressing | 31–33      |
| 6             | diamond               | naturally obtained, rapid pressurization, and pulse laser ablation | used in jewelry designing and biomedical field                           |                                       | 34–36      |
Ensuring efficiency and better utilization of nanotechnology is a constant challenge. Cultivation conditions, product stability, and marketability of microalgae-based products are still being refined. More research is needed on microalgal production’s long-term viability, economics, and environmental impacts. Concerns include energy consumption, production costs, yields, losses, and performance of overall microalgae biorefinery operations. CNMs can dramatically improve both biomass and carbon-based chemical accumulation in microalgae cultivation. Microalgae culture and treatment are costly and technically difficult processes in biorefinery. However, using CNMs can overcome this issue while maintaining high efficiency. In order to create a new generation of biofuels and microalgae products, this combination is constantly being investigated and tested.

Graphene oxide (GO) has been shown to efficiently catalyze the conversion of lipids to biodiesel from wet microalgae biomass. The conversion efficiency of these solid GO catalysts improved to 96% with increasing catalyst concentration but decreased with increasing temperature. The wet microalgae *Chlorella pyrenoidosa* was used to test the catalytic properties of graphene derivatives. Sulfonated graphene oxide (SGO) had the highest catalytic activity due to its greater hydrophilic hydroxyl content. Benefits include greater stability and recyclability. For better functionality, no need to filter the product, antibacterial properties, and easy controllability in certain reactors, enzyme-immobilized nanomaterials have been widely used in microalgae conversion. Multifunctionalization for integrated CNM utilization in microalgae biorefinery reduces overall process costs. Many studies have detailed using “upgraded nanoparticles” for harvesting, cell disruption, biomass extraction, and conversion. The carbonaceous shell can also separate microalgae 99% efficiently. Surface roughness and certain carbon functional groups could be used to create the lipophilic characteristic that attracts microalgae lipids. CNMs could be chemically stable and structurally diverse, with remarkable catalytic, redox, fluorescence, and luminescence properties.

**CNS: A NEW FRONTIER IN ALGAL GROWTH**

Recently, several CNMs such as CNS, owing to their enhanced productivity, nutrient availability, and tolerance to abiotic stress conditions, have revealed the potency of microalgae as energy-efficient bionano factories, playing a critical role in the development of biostimulant products related to pharmaceutical, nutraceutical, bioenergy, and environmental applications. Microalgae possess an autonomous solar energy harvesting capability equipped with self-repair and storage mechanisms. However, the far-reaching domain of biostimulant synthesis along with their physiochemical and molecular mechanisms upon interaction with CNS is still being investigated. Microalgae produce various biochemicals by harnessing solar energy through chlorophyll for cellular activities, where chlorophyll a (Chl a) and chlorophyll b (Chl b) are the major light-harvesting pigments. Chloroplasts facilitate the synthesis of carotenoids around the nucleus, while their accumulation is altered under stress conditions. The naturally occurring carotenoids are classified into carotenes and xanthophylls, which are hydrocarbons and oxygen derivatives of carotenes, respectively. Green microalgae (*Chlorella* sp.) hold the potential to produce high-value-added components, e.g., natural lipids and bioactive compounds, due to their superior characteristics such as rapid growth, facile cultivation, ability to grow under environmental stress conditions, and ample storage capacity. Strikingly, microalgae bioactive compounds such as lutein and β-carotene are in high demand predominantly in agricultural, food, and pharmaceutical industries. Advances in the synthesis of CNS and introducing them into the algal biosystem can boost its photosynthetic processes, thus tailoring the physicochemical functions of specific organelles which can act as molecular machineries for the production of bioactive compounds.

CNS are two-dimensional (2D) carbon-based materials, stacked or exfoliated in multilayers, primarily analogous to the structure of graphene, with high surface to volume ratio, excellent thermal and electrical properties, high chemical stability, thin edge plane defects, and lightness. Intriguingly, the passive internalization of CNS nanofragments is more favorable than any other modes of infiltration into algal cells, which can be attributed to their minimal damage to the cell membranes. Due to their excellent catalytic ability and nanocatalyst recovery, CNMs can also act as catalysts, as well as conversion-process lipases that produce high-quality products, in comparison to other conventional base or acid catalysts, whose recovery is difficult and requires the addition of chemicals. Pretreatment with CNMs has been shown to improve molecular chemical interactions and stimulate biocatalysis in certain targets. It also aids the release of microalgae internal components by allowing them to pass through cell membranes more easily. Because of the interaction between the CNMs and the cell walls, the incubation time for cell wall disruption was shortened at high CNM concentrations. Biomass preprocessing also necessitates an enzymatic hydrolysis treatment step that uses a variety of enzymes (cellulases, hemicellulases, and -glucosidases) to convert cellulose into monomeric sugars. Due to their large surface enlargement for better enzyme immobilization, applied metal nanoparticles can act as a support material in the immobilization step for improved enzymatic activity and stability, whereas conventional immobilization methods cause specific enzyme activities to decline during use. Nanomaterial-supported immobilized enzymes have the added benefits of reusability and recovery. The lower process costs allow for industrial scaling. Enzymes could also be immobilized by graphene oxide (GO) without the use of a cross-linking reagent, a surfactant, or any other surface modification. With the addition of a graphene oxide nanosupport, many enhancements such as improved enzymatic activity (at 70 °C), high solvent tolerance, thermal stability, durability, and reusability, as well as interenzyme binding and support have been established.

As an emerging technology, nanobionics support the incorporation of dynamic and adaptive functions to algal cell networks, influenced by the synergistic sustenance from CNS at the subcellular nanobio interface. They possess combinatorial novel functions that enhance sustainable biosynthetic pathways for the effective production of bioactive compounds. As reported, the entry of carbon nanotubes (CNTs) could not take place through the roots or stems in plants, attributed to their obstruction to the vascular flow, while they could enter through the leaves. Furthermore, CNTs are attracted to the chloroplast membrane, serving as the photosynthetic machinery which facilitates the absorption of light and the production of secondary carotenoids. However, a similar phenomenon does not occur in the case of metallic single-walled CNTs due to cytotoxic effects. Interestingly, revealing
useful processes for scavenging reactive oxygen species (ROS) can lead to promising protective mechanisms.49 The innovative experimental clues suggested that the heterogeneous platform comprising CNS coupled with biocompatibility can improve the stability of chloroplasts against ROS and stimulate the photosynthetic activities inside the algal cells for higher production of biomass, lipids, chlorophyll, and carotenoids.50

Generally, CNS are known to have properties like even and steady dispersibility in aqueous culture medium, exhibiting negligible light shading effects. Moreover, the noticeable Tyndal effect of CNS supports the uniform distribution of light in the medium, thus increasing microalgae growth. Surveys have revealed that this improved light absorption, owing to the light scattering effect within the culture medium, in the presence of CNS can advance the possibility of photons striking the chlorophyll, leading to more efficient photosynthesis. The growing phases of microalgae depend on existing nutrients and environmental factors. The photoautotrophic cultivation of microalgal cells is technically feasible for the fixation of CO₂, without any exposure of expensive and toxic organic solvents.51 In this study, algal cells were exposed to the CNS, which act as a heterogeneous platform to enhance the growth of microalgae (Scheme 1). CNS is an admirable adsorbent material in contrast to other carbon nanomaterials, which adsorb algae cells onto its surface and release the digestive enzymes for nutrient accomplishment, followed by the cell growth and lipid accumulation. Herein, the utilization of CNS in the algal growth established an ecofriendly approach targeting high yield of algal biomass and lipids for biofuel, nutraceutical, and other medicinal applications.50 Earlier reports suggested that CNS are exploited to boost the yield of bioactive compounds.52,53 One such wide approach to be employed for the augmentation of bioactive compound production, by supporting microalgal growth, is the incorporation of CNS.54 It can also be used to enhance the
photosynthetic performance of microalgae, by widening the spectral region accessible for the energy conversion reactions.

Based on the possible physiological and molecular mechanisms in the value chain of the algal production system, the nanobionics approach, reinforced by CNS, offers a cytoprotective role in the photosynthetic performance of microalgae with its tunability for augmenting the specific bioactive compounds. Moreover, this knowledge can be harnessed to control the precise positioning of CNS within photosynthetic systems and probe their interaction to empower them while regulating the negative carbon footprint.

**INTERACTION PROCESS OF ALGAL CELLS AND CNS**

Generally, nanoparticles smaller than the pore size of an algal cell wall (5–20 nm) can easily pass through it, while the movement of larger molecules is restricted. Additionally, the negatively charged functional groups present on the microalgal cell surface can facilitate the electrostatic attractions to some positively charged CNS. The interaction of CNS with microalgae cells is an intricate process that involves adsorption, internalization, and distribution of nanoparticles on the algal cell walls, through the membranes, and in the organelles, respectively (Scheme 2). The adsorption capacity of CNS on the algal cell surface depends on its morphology, concentration, rate of suspension, and duration of exposure. Endocytosis and passive transmission are the main pathways for internalization of CNS into the algal cells. Interestingly, while encapsulating nanomaterials, some microalgae generate extracellular polymeric substances (EPS) as a defense barrier. After entering into the microalgae cell, CNS spread in the extracellular polymeric substances (EPS) as a defense barrier. While encapsulating nanomaterials, some microalgae generate extracellular polymeric substances (EPS) as a defense barrier. The structure of CNS also possesses nitrogen-rich graphitic domains which are dominant due to higher catalytic activity plausibly resulting from the formation of CNS. This phenomenon could effectively induce the carbon partitioning processes in the growth of microalgae, which can be inferred from its growth curve data at 0.02–0.1 mg/mL concentrations of CNS (Figure 1). Interestingly, these concentrations have no inhibitory effect on algal cells for 30 days of CNS exposure. As a result, it is evident that CNS as a heterogeneous platform can critically improve the cell proliferation and production of bioactive compounds at various growth phases of microalgae. At the stationary phase, maximum biomass yield was achieved using 0.1 mg of CNS. From these growth curves, it is evident that our proposed theory helps in predicting the important role of pyridinic and graphitic nitrogen which influences the accumulation of lipid content from microalgae.

A collection of literature describes the utilization of CNMs, such as in multiwalled carbon nanotubes (MWCNT), graphene oxide nanosheets (GONS), graphene oxide quantum dots (GOQD), carbon nanotubes (CNT), and carbon dots (CD) for microalgal growth; however, the challenges lie in their inherent toxic nature. As reported earlier, the enhanced biomass (0.536 g/L, 0.814 g/L, and 17%) and lipid content (18%, 159 mg/g, and 130 mg/L) were produced using CNS, nanogels, and pristine CDs, respectively, without compromising their compatibility toward algal cells (Table 2).

The TEM image of a control algae cell with a clear intracellular structure with complete morphology is shown in Figure 2a. Although black sheets appeared in the algal cells cultured with CNS (0.08 and 0.1 mg/mL), the cell shape remains complete, and the intracellular structures of the algae were maintained (Figure 2b and c). Our findings exhibit better biocompatibility which is in quite contrary to the earlier reports utilizing carbon-based materials, where TEM analysis of *Chlorella vulgaris* exposed to different nanoparticles at 100 µg/mL for 48 h shows the inhibition of algal growth. Exposure of MWCNT and o-MWCNT on *Chlorella* sp. led to apparent plasmolysis, shrinkage of starch grains, larger pyrenoid, irreversible organelle damage, even cell vacuolation, and the appearance of lipid droplets. Furthermore, the morphological effect of CNS impinges on change in the efficacy of their cellular uptake.

**EFFECT OF CNMS ON INTRACELLULAR SUBSTRATES**

Commonly, the reactive oxygen species (ROS) generation in the advent of CNMs results in an excessive rate of lipid peroxidation, which directly affects the algal cell membrane system disrupting the normal function. Although algal species produce ROS as a byproduct of oxygen-based metabolic pathways (e.g., photosynthesis, oxidative phosphorylation, etc.), certain unfavorable conditions prevailing around algal cells (i.e., entry of foreign bodies) can induce oxidative stress, perturbing the oxygenic metabolism leading to the overproduction of ROS. Moreover, the oxidation of nucleic acids caused by ROS could result in mutagenesis. As a protective strategy, the algal biosystrem inherently produces ROS-
scavenging enzymes playing a critical role in the detoxification effect. Further, these ROS scavenging systems comprise enzymatic and nonenzymatic antioxidants, forming a defensive control in neutralizing the free radicals and their toxic effects.

Generation of antioxidant enzymes elevates the degree of elimination of ROS toxicity caused by the interaction of less toxic CNMs with algal cells, which in reverse collapses its
defense system at higher toxicity of CNMs during subcellular localization.

DOPING IN CNMS IMPROVE CATALYTIC ACTIVITY AND BIOCOMPATIBILITY

According to the nature of doping agents and synthetic procedures, heterostructured CNMs can be engineered for suitable catalytic reactions.50,68 Doping in CNMs is an effective way to tune their physicochemical properties including electrocatalytic activity,69 crystallinity,70 and conductivity,71 as well as enhancing their electrochemical stability and rapid ion transfer capability.72,73 Compared to their undoped counterparts, nitrogen-doped CNS have greatly enhanced photocatalytic activity along with higher biocompatibility which can be attributed to the presence of amino and hydroxyl groups.74,75 Moreover, our group has delineated the significance of graphitic-nitrogen (graphitic-N), a nitrogen atom at the junction of three hexagonal lattices, in obtaining higher lipid and biomass production without any lethal effect of nitrogen-doped CNS on algal growth. Interestingly, such versatile doping in CNS possesses a rich presence of graphitic-N domains along with pyridinic-nitrogen (pyridinic-N) and pyrrolic-nitrogen (pyrrolic-N), which can accelerate the nitrogen assimilation processes in microalgae (Scheme 1). Furthermore, the catalytic activity can be enhanced with the higher ratio of graphitic-N/pyridinic-N in CNS.50 Especially, the triazine moieties of these CNS possess better availability of electrons owing to their highly crystalline nature. Plausibly, the protonated amines, pyridine, and pyrrole moieties along with the graphitic domains of CNS can bolster the enzyme biosynthesis processes, where their accumulation might accelerate the production of pyruvate kinase (oxidative decarboxylation), ultimately accelerating the kinetics of metabolites during photosynthetic assimilation.

ROLE OF CARBON NANOMACHINERY IN SYNERGISTIC PROTECTION OF CHLOROPLAST AND MITOCHONDRIA

The oxygenic photosynthesis in microalgae is based on the conversion of solar energy to chemical energy by a series of electron transfer steps. The oxygen evolution center (OEC) is usually embedded within the thylakoid membranes of chloroplasts, located at the oxidizing side of PSII, providing a communication pathway (appraised as “Z scheme”) between internal organelles via the electron transport chain (Scheme 3). Interestingly, some nanoparticles were found to promote the oxidative photophosphorylation activity of chloroplasts, enhancing the chloroplast Hill reaction activity. Nanomaterials can increase the permeability of thylakoids and enable affluent transportation of ions (e.g., micronutrients) into the OEC complex.76 The abundance of green lamellae of thylakoids in algal chloroplasts promotes the activation of the electron transport chain around OEC complexes. The electron transport chain initiates redox reactions in the thylakoid membranes governed by PSII, PSI, cytochrome b6f, and ATP synthase complexes. Owing to the biocompatibility of P4 in C. sorokiniana, a flexible lipophilic environment prevails within thylakoid membranes allowing rapid diffusion of plastoquinone/plasto-hydroquinone (PQ/PQH2) through membrane face opening, between the protein environment of QA and plastoquinone pools. As a promising photocatalyst, the heterogeneity of CNS provides an avalanche of electron transport to the chloroplasts, inherently enhancing the “Z scheme” mechanism with superior redox shuttling centers.68

The excitation of PSII (P680) initiates the electron transfer to pheophytin which eventually passes via protein-bound plastoquinone (QA to QB).77 Moreover, the triazine moieties of CNS hold the affinity to bind with QA through hydrophobic interactions and hydrogen bonding to accelerate the electron flow, unveiling intense ATP synthesis. The additional nitrogen functionalities of CNS could prevent the blockage of electron flow to QA (permitting rapid quenching of excited states), in contrast to the typical interaction of triazine groups with the plastoquinone pool.77 The inherently constructed “Z scheme” junction of CNS can facilitate effective redox shuttling, inhibiting the photoinduced charge carrier recombination and fostering charge carrier transfers. The conductive domains of CNS can extend its absorption capacity from the visible light region and beyond, permitting conjugated π−π electron transfer through adsorption. Substantial N2 assimilation coupled with redox shuttling molecular systems enhances the synergism between chloroplast and mitochondria, enabling interorganelle signaling. The redox-dependent post-translational modifications can be constructed using CNS where the high proportion of redox-sensitive enzymes could regulate the central metabolic pathways such as photosynthesis, carotenoid biosynthesis, and nitrogen metabolism. Furthermore, these enzymes govern the redox signaling pathway transmitting information into metabolic pathways (e.g., glutathione, NADPH). Besides, these modulations enhance the mobility of electrons in the respiratory chain of mitochondrial metabolism bolstering the supply of reduced equivalents generated in the TCA cycle.

Generally, nitrogen and carbon metabolism plays a pivotal role in the algal cell proliferation specifically on the enhancement of several enzymatic biosynthesis processes. Intriguingly, employing CNMs in the algal biosystem can afford tailorable properties in the production of chlorophyll, carotenoids, and lipids. In the dark reaction, photosynthesis triggers a higher path rate to lipid production by rapidly converting glucose into proteins and subsequently into lipids.78 Fatty acid and triacylglycerol (TAG) syntheses are the two primary pathways for lipid biosynthesis. The metabolism of fatty acids has a remarkable influence on the Chl a biosynthesis, especially via upregulation of saturated fatty acids such as octadecanoic acid and hexadecenoic acid.79 The pyruvate molecules generated during this process can act as a central metabolite in guiding the carbon-alternative pathways and orienting the production of secondary metabolites along with other amino acids.80 The path rate of central carbon metabolism providing sufficient availability of the carbon molecules for the protein degradation via the tricarboxylic acid (TCA) cycle energizes the production of lipids and carotenoids. The regulation of carbon partitioning depends on the acclimation of algal cells due to intrinsic environmental changes, instigated by CNM exposure. Carbon rerouting to starch, glycerolipids, and isoprenoids occurs based on the differential cellular compartmentalization of essential reactions of glycolysis under cellular stress conditions.81 Thus, the entry of CNMs into the algal biosystem greatly influences the carbon partitioning process, which plays a key role in governing the enzymatic activities in microalgae and the production of bioactive compounds.
FUTURE PROSPECTS IN THE DEVELOPMENT OF ALGAL NANOBIONICS

To gain insight into the intrinsic metabolic changes at the nanobio interfaces using the algal nanobionics approach is imperative to understand the interconnected mechanisms that ameliorate the production of lipids and carotenoids. In this regime, CNS can help to establish a facile conduit in regulating the major functions of the endoplasmic reticulum mainly in the formation of TAG, EPS, and lipid droplets wherein oxidative stress in microalgae unveils the significance of intracellular ROS. Notably, the CNS exposure and the ratio of saturated to unsaturated fatty acids can govern the membrane fluidity. Moreover, unraveling the strategies behind the carbon and nitrogen assimilation in the presence of CNS can enhance the production of secondary metabolites, leading to high yield of bioactive compounds. The structural integrity of CNS endures progressive evolution with specific functionalities in the field of metal-free artificial photocatalysis for solar energy harvesting particularly in microalgae systems. The interaction of nanomaterials with the algal systems could lead to more complex nanobiohybrid organisms, also called “algal nano-biohybrids”, augmented with superior performance features. Algal nanobiohybrids could establish sustainability in enormously growing medical, pharmaceutical, and agricultural sectors.

SUMMARY AND OUTLOOK

Herein, we have aimed to provide comprehensive and conceptual insights into the production of various biostimulant products through an “algal nanobionics” approach which may act as a “great balancing pillar” to bridge the food gap by reinforcing economic development and reducing the environmental burden while supporting a sustainable selection of foods. This mini-review draws attention to the unexplored properties of CNMs for efficient algal growth under the photoautotrophic mode of cultivation. Plausibly, the entry of CNS into the algal biosystem confers novel functional properties and governs the electron transfer rates in the chloroplast photosynthetic machinery through rapid harvesting of solar energy, thereby presenting a sustainable alternative for the extraction of various bioactive compounds. A growing body of investigation has confirmed that these bioactive compounds play pivotal roles in the prevention (and even cure) of several human diseases and health conditions, e.g., cancer, cardiovascular problems, atherosclerosis, rheumatoid arthritis, muscular dystrophy, cataracts, and numerous neurological disorders. Key features such as their intrinsic antioxidant, anti-inflammatory, and antitumor predispositions account for their favorable biological activities. Consequently, the synergy between algae and CNS can open new horizons in interfacial bioinspired engineering for reshaping the presently available extraction methods for bioactive compounds and energy harvesting applications and by initiating the possibility of producing stable synthetic materials that can self-repair and reproduce using sunlight as the vital source.

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