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Review

Harnessing photosynthesis for materials, devices, and environmental technologies

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Photosynthetic organisms convert solar light into chemical energy through the process of photosynthesis. The employment of photosynthetic organisms in novel materials and devices provides them with a solar-powered and sustainable functionality. In general, photosynthesis utilizes light, water, and CO_2 to generate various organic compounds while releasing secondary valuable products such as O_2, extracellular electrons, carbohydrates, or H_2. The light-dependent inputs and outputs are harnessed for environmental purification, biomedical applications, and production of biofuel, electricity, nanomaterials, or bioplastics. In this review, we summarize photosynthesis-assisted materials and engineering applications based on the products and substrates of photosynthetic processes, and we highlight key challenges that remain to be addressed.

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Introduction

Photosynthetic organisms convert light into chemical energy through photosynthesis, serving as the primary producers at the foundation of many ecosystems and food chains. Oxygenic organisms (plants, algae, certain types of cyanobacteria) use water and CO_2 to produce carbohydrates with O_2 as a byproduct (Reaction 1) [1].

$$2H_2O + CO_2 + \text{light} \rightarrow (CH_2O)_n + H_2O + O_2 \quad (1)$$

Complex biochemical processes are involved in carrying out these seemingly simple chemical reactions in photosynthesis. Reactants and end products of photosynthesis as well as underlying regulative mechanisms can be utilized in light-driven materials and devices, while endowing sustainable, biocompatible or regenerative features difficult to achieve in traditional systems.

This paper gives an overview of technologies that directly or indirectly utilize photosynthesis. First, the biological process of photosynthesis is presented with focus on the main reactants and end products. Then, applications associated with photosynthetic reactants (CO_2), photosynthetic end products (O_2, carbohydrate), or photosynthetic regulative mechanisms (electron export, H_2) are presented.

Reactants and end products of photosynthesis

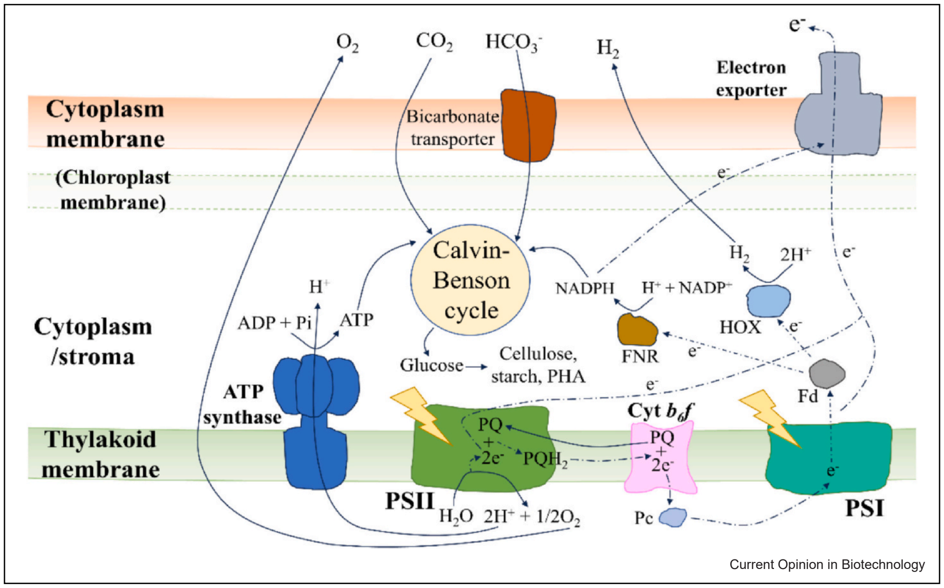
Light reaction

Photosynthesis is divided into the light reaction and the dark reaction (Figure 1). The light reaction starts in a transmembrane protein complex located in thylakoid membranes of cyanobacteria and chloroplasts called photosystem II (PSII), where photons excite electrons in chlorophyll pigments. The energy is passed from pigment to pigment until it reaches the chlorophyll of the P680 reaction center. After P680 excitation, an electron is released into the photosynthetic electron transport chain, resulting in the formation of cationic $P680^+$. The missing electron of $P680^+$ is replaced through the splitting of water at the O_2 evolving complex located in the luminal part of PSII. Each water molecule releases 2 electrons to regenerate P680 with ½ O_2 and $2H^+$ as biproducts (Reaction 2). While some O_2 is used for respiration, the majority diffuses to the extracellular environment.

$$2H_2O + \text{Light} \rightarrow O_2 + 4H^+ + 4e^- \quad (2)$$

Plastoquinone (PQ), a hydrophobic electron carrier, collects two excited electrons at PSII and is converted to plastoquinol (PQH_2). PQH_2 then diffuses through the thylakoid membrane to cytochrome b_6f complex (Cyt b_6f), where PQH_2 molecules are oxidized and transfer electrons to hydrophilic, luminal electron carriers plastocyanin (Pc) or cytochrome c_6 (Cyt c_6). This process releases energy and fuels the dislocation of H^+ to the lumen at Cyt b_6f, contributing to the H^+ gradient across the thylakoid membrane. Pc or Cyt c_6

Figure 1



Schematic diagram of biological processes involved in light reaction, carbohydrate production, hydrogen production, and electron export in a photosynthetic cell. Dotted lines indicate electron transport pathways. Photosystem II (PSII), photosystem I (PSI), cytochrome b_6f complex (Cyt b_6f), hydrogenase complex (HOX), ferredoxin (Fd), ferredoxin-NADP$^+$ reductase (FNR), polyhydroxyalkanoate (PHA). Electron export is displayed vaguely since underlying electron carriers and transporters vary between lineages and/or are poorly understood.

transfers the electrons to photosystem I (PSI). PSI works in a similar manner to PSII, and the electrons excited here are transferred to ferredoxin (Fd) located at the stromal side of PSI. Fd donates electrons to ferredoxin-NADP$^+$ reductase (FNR), which in turn reduces NADP$^+$ to NADPH.

The H$^+$ gradient facilitated at the thylakoid drives a transmembrane protein complex called ATP synthase. Here, the H$^+$ in the lumen follow their electrochemical gradient and return through the ATP synthase to the stroma. This drives a spectacular molecular machinery that regenerates ATP.

Dark reaction

In the dark (=light independent) reaction of photosynthesis, inorganic carbon is fixed into organic carbohydrates through the Calvin-Benson cycle (CBC; Reaction 3). This reaction takes place in the stroma of chloroplasts or cytosol of cyanobacteria.

In aquatic environments, the predominant type of dissolved inorganic carbon (DIC) depends on pH (acidic: H_2CO_3/CO_2; neutral: HCO_3^-; alkaline: CO_3^{2-}). DIC either diffuse passively or are transported actively (carbon concentrating mechanism) to the CBC. Then, the enzyme ribulose-1,5-bisphosphate carboxylase-oxygenase fixes molecular CO_2 into the C5-sugar ribulose-1,5-bisphosphate, creating two C3-sugars of 3-phosphoglycerate. Subsequent steps of the CBC require NADPH and ATP from the light reaction, eventually forming the C6-sugar glucose. Glucose can be further processed into polysaccharides for energy storage (starch) or building blocks (cellulose).

$$CO_2 + 4H^+ + 4e^- \rightarrow (CH_2O)_n + H_2O \quad (3)$$

Applications based on photosynthetically produced O_2

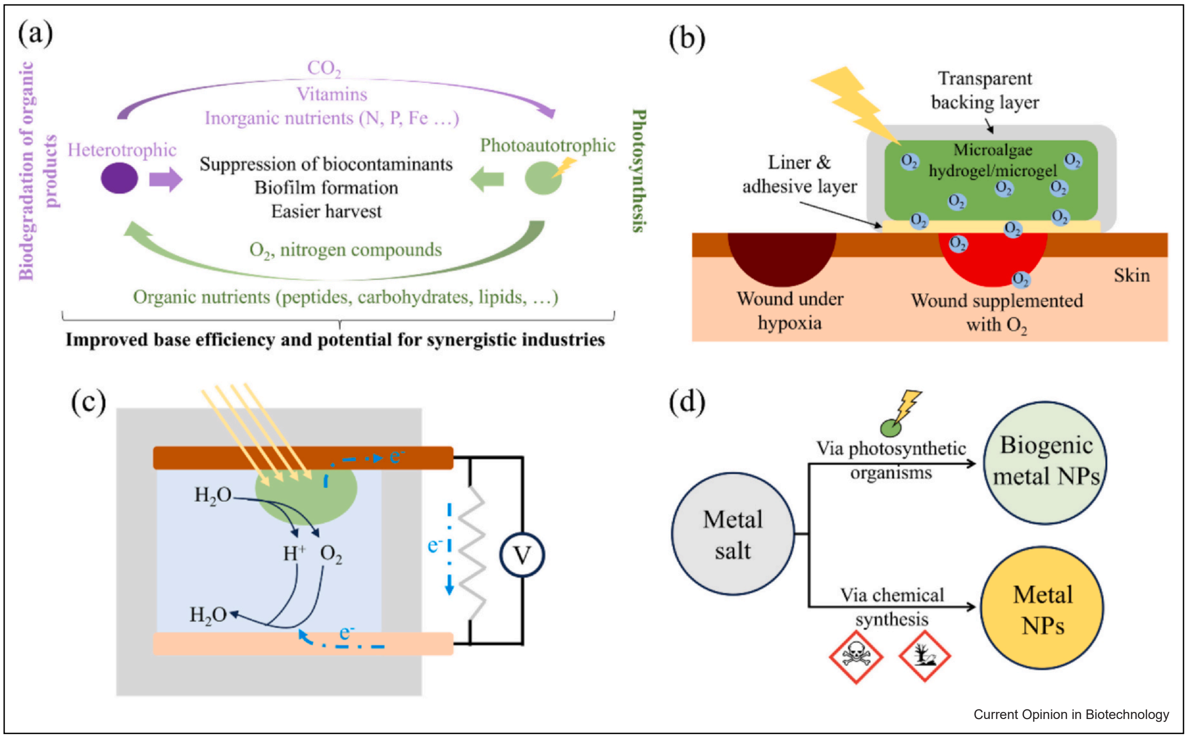
Any organism performing aerobic respiration uses O_2 as final electron acceptor, forming H_2O. Various industrial and medical applications demonstrate the increased performance of respiring cells when O_2 is supplied by photosynthetic organisms (Figure 2a,b) [2,3].

Photosynthetic organisms in synergistic industries

Co-culturing photosynthetic and respiratory organisms in symbiotic consortia is explored in industry for increased efficiency, robustness toward biocontamination (e.g. outgrowth), self-reliance (e.g. vitamin/nutrient exchange), or scalability of both heterotrophic and autotrophic partner alike (Figure 2a).

For example, O_2 supplied by photosynthetic organisms in municipal wastewater treatment reduces total energy requirement by 40–60% [4], as it eliminates the need for artificial aeration while still allowing biological oxidation of organic matter by aerobic microorganisms. Moreover, the presence of microalgae improves the assimilation of

Figure 2



Applications based on photosynthetically generated O_2 and electrons. **(a)** Symbiotic relationship between heterotrophic and phototrophic processes for synergetic industries. **(b)** Microalgal hydrogel/microgel medical patch that releases oxygen to wound under hypoxia. **(c)** Design of biophotovoltaic systems used to harvest bioelectricity from an oxygenic biofilm attached to an anode. An anode receives electrons from photosynthetic organisms, and a catalytic cathode enables the terminal electron acceptor reaction (e.g. $O_2 + 2H^+ \rightarrow H_2O$). **(d)** Chemical synthesis and photosynthesis for producing metal nanoparticles (NPs) from metal salts.

excess nitrogen or phosphate species up to 90% [5]. Similarly, including microalgae in aerobic microbial fuel cells eliminates the need for artificial aeration to supply O_2 as the final electron acceptor at the cathode. Additionally, algae provide nutrients or O_2 to electrochemically active microorganisms at the anode.

Further promising examples in which microalgae assist bacteria through O_2 supply include bioremediation [6], production of biofuels [7], or biogas purification [2]. Likewise, bacteria can also assist algae, for which some examples will be presented in the following sections. However, a common limitation is the challenge of matching growth rates of symbiotic partners under changing environmental conditions (e.g. light access), which can introduce competition or toxicity effects (e.g. pH, NH_3, etc.) if unbalanced.

Photosynthetic organisms in medical applications

Both chronic wounds and cancer tissues are characterized by hypoxia due to damage or outgrowth of vascular systems, respectively. Localized supplementation of O_2 is occasionally employed for wound and cancer treatments, but techniques vary greatly in dose control, continuity in O_2 supply, convenience, side effects, or costs. These include high-pressure chambers, electric O_2 generators, or chemicals [8]. Among these, a relatively convenient approach is described as chemical oxygen production therapy, which provides O_2 through administration of nanoparticles (NPs) or H_2O_2-decomposing nanocarriers [9] but poses challenges related to low control of lifetime, dosage, or spatial distribution.

Microalgae are explored as an alternative to improve local O_2 supply in wounds [10–12] (Figure 2b) and cancer tissues [3,13,14]. They are typically incorporated into hydrogels or microspheres [15] to improve administration, lifetime, and diffusion of dissolved O_2. Some gel polymers such as pluronic F-127 can be printed, enabling control over 3D shape and direct deposition into wound beds [16]. Low surface attachment of gels is a reoccurring problem but was improved by including adhesives such as chitosan [17] or polydopamine [16]. Co-culture of biocompatible bacteria and microalgae was shown to improve healing and inhibit infections [16].

Instead of using patches and hydrogels, mobile cells were also tested. Nonmotile microalgae coated with superparamagnetic Fe_3O_4 NPs were steered directly to the desired location with magnetic fields [10]. Other approaches utilize inherent mobility of microalgae — not only to deliver O_2 to the target site but also to deliver other useful substances (e.g. heparin) and to improve mixing [18]. The generally high biocompatibility of microalgae was further improved by cloaking them in membranes of red blood cells [3]. Even dead microalgae demonstrated to be useful since chlorophyll works similar to light-absorbing 'photosensitizers' utilized in conventional photodynamic cancer therapy [3] in that they both donate electrons to O_2 upon light excitation, forming reactive oxygen species (ROS).

Applications based on photosynthetically generated electrons

Photosynthetic organisms produce excessive electrons under certain conditions. When exposed to high light or low CO_2, an imbalance between generation of electrons and reduction of $NADP^+$ occurs. If unaddressed, those excess electrons leak out of the chain and react with O_2, forming ROS that damage cell components [19]. Therefore, exporting mechanisms for excess electrons exist, which differ in detail between the photosynthetic lineages (Figure 1): eukaryotes mostly rely on NADPH oxidases, while prokaryotes rely on protein nanowires (type IV pilus) located at the plasma membrane [19,20]. Extracellular electrons rapidly react with the environment, either forming ROS or reducing metals. Such photosynthetically generated electrons are used in several applications.

Biological photovoltaic system

Several types of electrogenic devices exist, which are categorized by the type of organism employed. Photosynthetic or symbiotic microbial fuel cells (PMFCs) use either photoheterotrophic organisms alone or a consortium of both heterotrophic and photoautotrophic organisms to generate electricity using light. These approaches either require heterotrophic metabolisms to produce electrons on anodes or external supplementation of electron acceptors such as O_2 on cathodes [21]. In contrast to PMFCs, biological photovoltaic (BPV) systems use only oxygenic, photoautotrophic organisms, which generate electrons via photolysis of water and produce their own electron acceptors in the form of O_2 (Figure 2c) [22].

As exemplified in Figure 2c, a typical BPV device consists of a transparent chamber for oxygenic photosynthetic organisms, a transparent anode (e.g. indium tin oxide–coated polyethylene terephthalate), and a catalytic metal cathode like platinum [20]. In some devices, a soluble electron carrier like $K_3[Fe(CN)_6]$ collects electrons from the liquid medium and donates them to the anode, while in other devices, this step is bypassed by immobilizing cells at the anode in biofilms or hydrogels [23,24]. The electrons flow from the anode through an external circuit to the cathode, creating electricity to power other devices or to be stored in batteries. O_2 and protons produced during photosynthesis diffuse to cathodes, receiving electrons from cathode and forming water. BPVs' energy output is not yet comparable to Si-based voltaic systems. For improving BPVs, promising approaches include directly extracting electrons from photosystems via exogenous electron mediators (rewired photosynthesis) and employing biogenic anode materials [25,26].

Biosynthesis of metal nanoparticles

Metal NPs are typically smaller than 100 nm and exhibit unique physical and chemical properties. They are widely utilized in medical diagnosis, wound care, electron microscopy, and electronics fabrication. Traditional synthesis methods, such as chemical reduction, sol-gel, and hydrothermal synthesis, come with environmental hazards and may introduce toxic impurities in NPs.

Biosynthesis of NPs via photosynthetic organisms excludes environmental hazards and improves biocompatibility (Figure 2d) [27]. In the presence of light, metal NPs can be biosynthesized via electron transport chain on thylakoid membranes by photosynthetic organisms [28]. Metal NPs were shown to accumulate in chloroplasts of eukaryote cells exposed to metal ions [29]. While the exact mechanism is still being investigated, electrons donated from electron transport chain on thylakoid membranes can convert metal ions into metal precipitates, eventually forming metal NPs. For instance, administration of $HAuCl_4$ (or $AgNO_3$) to a microalgae or cyanobacteria culture allows biosynthesis of gold (or silver) NPs in sufficient quantities to cause a color shift in these cultures [30,31].

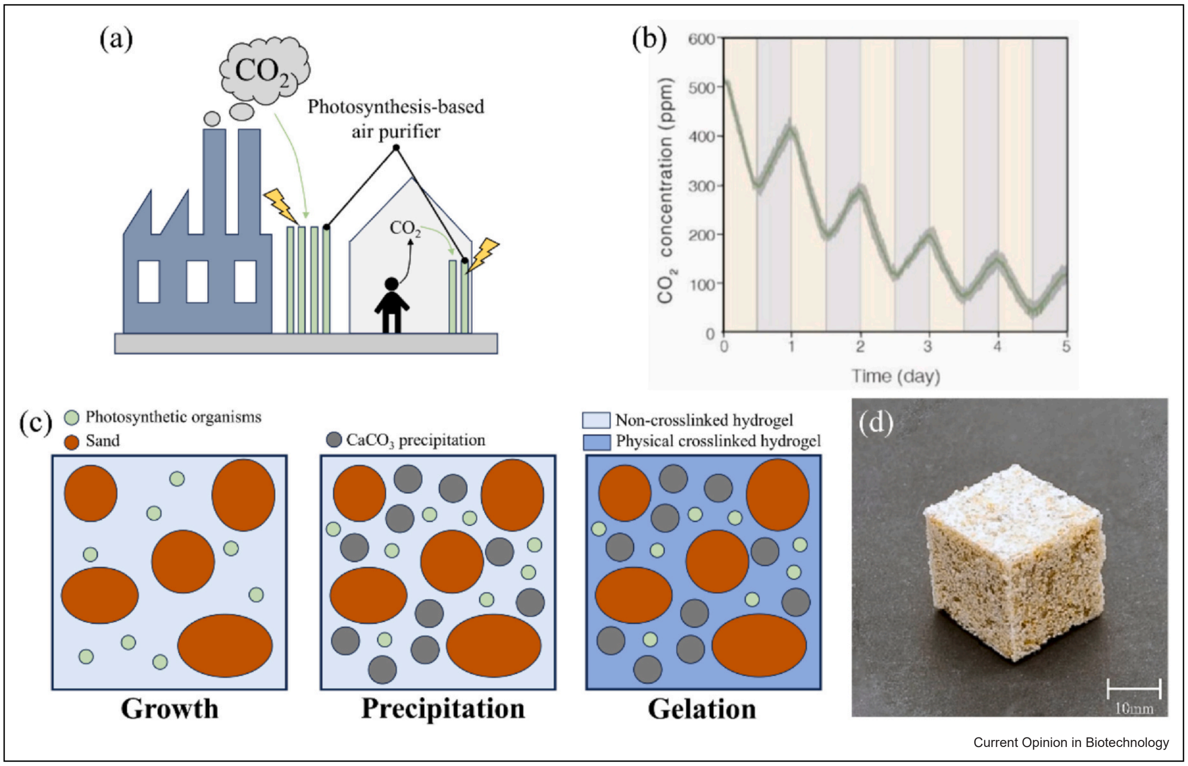
Applications based on CO_2 capture

Approximately 25% of yearly anthropogenic C emissions are compensated by forest ecosystems, exemplifying both magnitude of emissions and value of photosynthesis [32]. Although the employment of plants or microalgae inherently adds an element of environmental sustainability to any application, some applications emphasize this aspect more than others.

Improvement of air quality

Greenhouse gases or pollutants (CO_2, NO_X, SO_X, volatile organic compounds, *etc.*) impact both human health and climate. Poorly ventilated indoor environments often show elevated CO_2 levels compared to outdoor ambient air levels, with measurable effects on human health above 1000–5000 ppm [35]. Physicochemical air cleaning devices (e.g. filters, fuel cells, catalyzers) help lowering emission of pollutants and improving air

Figure 3



Applications based on photosynthetically capturing of CO_2. **(a)** Concept of photosynthesis-based air purifiers designed to reduce outdoor and indoor CO_2 emissions. **(b)** Five-day monitoring of CO_2 consumption curve of a seven-day old living photosynthetic hydrogel cube under alternating periods of light exposure (beige background) and darkness (gray background) [33]. **(c)** Schematic of $CaCO_3$ precipitation in sand/hydrogel scaffold with photosynthetic microorganisms. **(d)** Image of a sand/hydrogel scaffold with cyanobacteria [34].
(b) With permission from Advanced Materials. **(d)** With permission from Construction and Building Materials.

quality, but they are prone to clogging, difficult to recycle, or require electricity to operate [36].

In addition to being efficient at biofixation of CO_2, plants and microalgae are able to transform, accumulate, or assimilate a range of other pollutants (Figure 3a) and are therefore occasionally described (and sold) as 'air purifiers' [37]. Microalgae immobilized in hydrogels enable portability and shape control via 3D printing [38–40] and benefit from improved gas exchange and light penetration, thus improved CO_2 fixation and O_2 production (Figure 3b) [33,41]. The CO_2 capture efficiency of cyanobacteria also increases when grown inside porous 3D ceramics, which provide large effective surface areas for illumination [42]. However, it remains to be seen whether these devices are consumer-friendly and practical enough for wider application. Compared to microalgae, plants have a lower net growth rate but also represent a low-maintenance-cost option suitable for private use. The superior productivity of microalgae unfortunately manifests in higher maintenance costs, ranging from 300 to 50 000 $ per year for a household or public photobioreactor [43].

Photosynthesis-assisted living building materials

Cement production contributes 7% to global anthropogenic CO_2 emissions due to sintering of limestone and clay [44]. Hence, eco-friendly concretes are being explored, for example, via microorganism-induced calcium carbonate precipitation (MICP). MICP often uses ureolytic bacteria to precipitate $CaCO_3$ from Ca^{2+} ions for biogenic concrete [45]. However, unfavorable NH_3 gas is released in this process, and the low viability of ureolytic bacteria in high-pH environments hinders long lifespan.

Photosynthetic microorganisms are explored to fabricate living building materials (LBMs) that can grow and self-heal. In this case, cells import HCO_3^- to concentrate CO_2 (Figure 1) and export OH^-, raising pH to alkaline levels and promoting $CaCO_3$ precipitation without NH_3 emissions (Figure 3c) [46]. The carbon source for $CaCO_3$ precipitation can also originate from atmospheric CO_2, omitting HCO_3^- addition, and improving environmental sustainabely of LBMs [34]. Cyanobacteria-induced $CaCO_3$ precipitation can mineralize and toughen LBMs, as shown with sand/gelatin LBM containing cyanobacteria (Figure 3d). The embedded microorganisms may also endow materials with regenerative properties, sealing cracks through biomineralization, with 30-day viability within the scaffold [46].

Applications based on photosynthetically produced carbohydrates

Carbohydrates derived from photosynthesis have been essential to humans as a source of food, building materials, and clothing since ancient times. Recently, carbohydrates are explored to fabricate bioplastics based on chemically modified cellulose, gelatinized starch, or polyhydroxyalkanoate, emerging as sustainable and biodegradable alternatives of petrochemical plastics. Since bioplastics produced by photosynthetic organisms were reviewed elsewhere [47], we focus instead on photosynthetically produced carbohydrates used for light-responsive polymer remodeling and for waste treatment.

Mechanical properties of materials often deteriorate with time due to degradation and fatigue. Carbohydrates generated via photosynthesis can help to remodel and enhance materials' stiffness (Figure 4a). In a recent photosynthetic living material, glucose locally released from chloroplasts was used to crosslink and strengthen a polymer matrix when illuminated. Hydroxyl groups (-OH) from glucose could interact with isocyanate groups (-NCO) in the hydrogel to form strong urethane linkages (-NH-CO-O-) (Figure 4b) [48]. Alternatively, glucose can be converted into gluconolactone by glucose oxidase (GOx), introducing reactive carbonyl-group (-C=O) groups. These can polymerize with hydrogel polymers containing primary amine groups (-NH_2) such as poly(aminopropyl methacrylamide) [49], facilitating a living material that strengthens and self-repairs via CO_2 fixation in the presence of light.

Carbohydrate production by photosynthetic organisms is also used in bioreactors for wastewater treatment. Cattle manure leachate (CML) represents a biodegradable type of wastewater with organic pollutants. Methanogens can use nutrient-rich CML as substrate for CH_4 production via anaerobic digestion while biodegrading organic pollutants. However, the efficiency of hydrolysis, acidogenesis, acetogenesis, and methanogenesis are limited due to unfavorable low-C and high-N concentrations in CML [50]. Anoxygenic phototrophic purple nonsulfur bacteria [51] can be employed to assist in anaerobic digestion of methanogens in bioreactor devices (Figure 4c) indirectly through photosynthesis, producing carbohydrates and shifting the C:N ratio to more favorable levels. The production rate of CH_4 hereby directly correlates with illumination [52].

H_2 production

H_2 is discussed as a clean energy carrier, but its large-scale production remains a challenge. Since no naturally occurring sources of easily extractable H_2 exist in high quantities, finding sustainable methods for its mass production is crucial. Photosynthetic microorganisms can produce H_2 through two separate pathways.

In one pathway, electrons from the photosynthetic light reaction are donated via Fd to the hydrogenase complex (HOX), which directly forms H_2 while consuming H^+ (Figure 1, Reaction 5). However, since HOX is sensitive to oxygen, H_2 production ceases during prolonged photosynthetic activity. Efforts to circumvent this include sulfur deprivation, aiming to suppress PSII activity and thus oxygen generation [53], as well as employing a microalga mutant strain that decreases oxygen generation via a deficient cyclic electron flow and higher respiration activity [54]. Immobilization of cells in materials such as alginate and linen-like glass fibers also strives to increase cell density and shield cells from atmospheric O_2 [55,56]. The second pathway is based on the enzyme nitrogenase employed by N_2-fixing cyanobacteria. Without a sufficient nitrogen source (e.g. NH_4^+), N_2 is converted under high ATP investment to NH_3, which releases H_2 as byproduct (chemical Reaction 6) [57]. However, neither pathway currently produces H_2 in sufficient quantities allowing scalability.

$$2H^+ + 2Fd^- \xrightarrow{\text{Hydrogenase}} H_2 + 2Fd \tag{5}$$

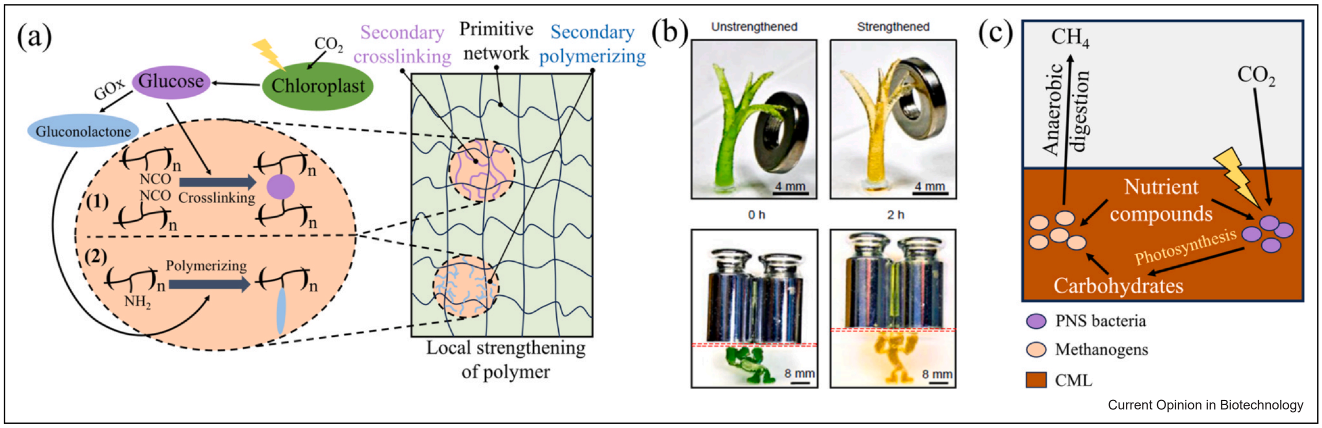
$$N_2 + 8H^+ + 8e^- + 16ATP \xrightarrow{\text{Nitrogenase}} 2NH_3 + H_2 + 16ADP + 16Pi \tag{6}$$

Conclusion and outlook

In this paper, the recent development of photosynthesis-assisted technologies was summarized, with applications in material fabrication, electricity generation, biomedicine, environmental improvement, or fuel production. Many of these applications share similar challenges that currently hamper their wider use.

(1) Financial aspects: Similar to plants in greenhouses, providing optimal conditions for microalgae also increases maintenance costs. CO_2 capture — associated with most applications — does not come with immediate monetary value, so it is rarely included in cost calculations. This might partially explain why only high-value high-biomass products such as pigments have gained traction in industry, while low-value high-biomass products such as biofuels remain unestablished [58]. Several options to improve efficiencies exist. Genetic engineering led to more productive strains, albeit within the limits of respective biological systems [59]. Another approach would be to combine the manifold applications into symbiotic, synergistic industries, for example, photosynthesis-assisted wastewater treatment followed by cell extraction for bioplastics.

Figure 4



Applications based on photosynthetically produced carbohydrates. **(a)** Schematic showing glucose produced by chloroplasts promoting cross-linking/polymerizing of hydrogels for increased structural integrity in hydrogels. **(b)** Images demonstrating the enhanced structural stability of chloroplast-containing 3D hydrogels when reinforced with photosynthesis-produced glucose [48]. **(c)** Schematic of photosynthesis-assisted conversion of manure waste into CH_4. PNS bacteria, purple nonsulfur bacteria.
(b) With Permission from Proceedings of the National Academy of Sciences.

(2) Ensuring performance stability and lifetime: Most industrial applications desire reliable, reproducible, and steady long-term performance difficult to achieve with living organisms that continuously adjust their metabolism to their environment. The reliance of photosynthesis on illumination can serve as a control feature, but its variability needs to be considered (e.g. wound patches under clothing or opaque wastewater). Most applications would likely benefit from bioreactor-like setups that allow continuous addition of nutrients and removal of biomass. The low lifetime of some photosynthetic materials and devices described here highlights the requirement of either more durable organisms or more sophisticated water and nutrient delivery systems.

Continuing the current trend of increasing interdisciplinary collaboration, including biologists, engineers, and chemists, will hopefully lead to solutions that assert themselves in the market.

CRediT authorship contribution statement

Fan Jiang: Conceptualization, Writing – original draft preparation, Visualization. **Friedrich Hans Kleiner**: Conceptualization, Writing – original draft preparation, Supervision. **Marie-Eve Aubin-Tam**: Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Pessarakli M: **Handbook of Photosynthesis**. 4th ed, CRC press; 2024, https://doi.org/10.1201/b22922

2. Xu M, Xue Z, Sun S, Zhao C, Liu J, Zhao Y: **Co-culturing microalgae with endophytic bacteria increases nutrient removal efficiency for biogas purification**. *Bioresour Technol* 2020, **314**:123766, https://doi.org/10.1016/j.biortech.2020.123766

3. Qiao Y, Yang F, Xie T, Du Z, Zhong D, Qi Y, Li Y, Li W, Lu Z, Rao J, Sun Y, Zhou M: **Engineered algae: a novel oxygen-generating system for effective treatment of hypoxic cancer**. *Sci Adv* 2020, **6**:eaba5996, https://doi.org/10.1126/sciadv.aba5996

4. Nguyen TKL, Ngo HN, Guo W, Chang SW, Nguyen DD, Nghiem LD, Liu Y, Ni B, Hai FI: **Insight into greenhouse gases emissions from the two popular treatment technologies in municipal wastewater treatment processes**. *Sci Total Environ* 2019, **671**:1302-1313, https://doi.org/10.1016/j.scitotenv.2019.03.386

5. Daverey A, Pandey D, Verma P, Verma S, Shah V, Dutta K, Arunachalam K: **Recent advances in energy efficient biological treatment of municipal wastewater**. *Bioresour Technol Rep* 2019, **7**:100252, https://doi.org/10.1016/j.biteb.2019.100252

6. Safonova E, Kvitko KV, Iankevitch MI, Surgko LF, Afti IA, Reisser W: **Biotreatment of industrial wastewater by selected algal-**

bacterial consortia. *Eng Life Sci* 2004, **4**:347-353, https://doi.org/10.1002/elsc.200420039

7. Leong WH, Kiatkittipong K, Kiatkittipong W, Cheng YW, Lam MK, Shamsuddin R, Mohamad M, Lim JW: **Comparative performances of microalgal-bacterial co-cultivation to bioremediate synthetic and municipal wastewaters whilst producing biodiesel sustainably**. *Processes* 2020, **8**:1427, https://doi.org/10.3390/pr8111427

8. Gottrup F, Dissemond J, Baines C, Frykberg R, Jensen PØ, Kot J, Kröger K, Longobardi P: **Use of oxygen therapies in wound healing: focus on topical and hyperbaric oxygen treatment**. *J Wound Care* 2017, **26**:1-43, https://doi.org/10.12968/jowc.2017.26.Sup5.S1

9. Sun X, Yao F, Zhang H, Li J: **Oxygen-generating materials and their biomedical applications: a review**. *J Mater Sci* 2022, **57**:9077-9103, https://doi.org/10.1007/s10853-022-07229-1

10. Zhong D, Li W, Qi Y, He J, Zhou M: **Photosynthetic biohybrid nanoswimmers system to alleviate tumor hypoxia for FL/PA/MR imaging-guided enhanced radio-photodynamic synergetic therapy**. *Adv Funct Mater* 2020, **30**:1910395, https://doi.org/10.1002/adfm.201910395

11. • Chen H, Cheng Y, Tian J, Yang P, Zhang X, Chen Y, Hu Y, Wu J: **Dissolved oxygen from microalgae-gel patch promotes chronic wound healing in diabetes**. *Sci Adv* 2020, **6**:eaba4311, https://doi.org/10.1126/sciadv.aba4311.

The study demonstrates a novel microalgae-gel patch, which is capable of continuously delivering oxygen via photosynthesis to enhance wound healing. The patch accelerates healing through improved oxygenation, cell proliferation, and angiogenesis, offering a cost-effective and non-invasive therapeutic strategy for diabetic foot ulcers and potentially other regenerative applications.

12. Wang X, Yang C, Yu Y, Zhao Y: **In situ 3D bioprinting living photosynthetic scaffolds for autotrophic wound healing**. *Research* 2022, **2022**:9794745, https://doi.org/10.34133/2022/9794745

13. Huo M, Wang L, Zhang L, Wei C, Chen Y, Shi J: **Photosynthetic tumor oxygenation by photosensitizer-containing cyanobacteria for enhanced photodynamic therapy**. *Angew Chem Int Ed* 2020, **59**:1906-1913, https://doi.org/10.1002/anie.201912824

14. Wang H, Liu H, Guo Y, Zai W, Li X, Xiong W, Zhao X, Yao Y, Hu Y, Zou Z, Wu J: **Photosynthetic microorganisms coupled photodynamic therapy for enhanced antitumor immune effect**. *Bioact Mater* 2022, **12**:97-106, https://doi.org/10.1016/j.bioactmat.2021.10.028

15. Stapleton LM, Farry JM, Zhu Y, Lucain HJ, Wang H, Paulsen MJ, Totherow KP, Roth GA, Brower KK, Fordyce PM, Appel EA, Woo YJ: **Microfluidic encapsulation of photosynthetic cyanobacteria in hydrogel microparticles augments oxygen delivery to rescue ischemic myocardium**. *J Biosci Bioeng* 2023, **135**:493-499, https://doi.org/10.1016/j.jbiosc.2023.03.001

16. Chen G, Wang F, Zhang X, Shang Y, Zhao Y: **Living microecological hydrogels for wound healing**. *Sci Adv* 2023, **9**:eadg3478, https://doi.org/10.1126/sciadv.adg3478

17. Li W, Wang S, Zhong D, Du Z, Zhou M: **A bioactive living hydrogel: photosynthetic bacteria mediated hypoxia elimination and bacteria-killing to promote infected wound healing**. *Adv Ther* 2021, **4**:2000107, https://doi.org/10.1002/adtp.202000107

18. Choi H, Kim B, Jeong SH, Kim TY, Kim DP, Oh YK, Hahn SK: **Microalgae-based biohybrid microrobot for accelerated diabetic wound healing**. *Small* 2023, **19**:2204617, https://doi.org/10.1002/smll.202204617

19. Lea-Smith DJ, Bombelli P, Vasudevan R, Howe CJ: **Photosynthetic, respiratory and extracellular electron transport pathways in cyanobacteria**. *Biochim Et Biophys Acta (BBA) Bioenerg* 2016, **1857**:247-255, https://doi.org/10.1016/j.bbabio.2015.10.007

20. Anderson A, Laohavisit A, Blaby IK, Bombelli P, Howe CJ, Merchant SS, Davies JM, Smith AG: **Exploiting algal NADPH oxidase for biophotovoltaic energy**. *Plant Biotechnol J* 2016, **14**:22-28, https://doi.org/10.1111/pbi.12332

21. Apollon W, Luna-Maldonado AI, Kamaraj SK, Vidales-Contreras JA, Rodríguez-Fuentes H, Gómez-Leyva JF, Aranda-Ruíz J: **Progress and recent trends in photosynthetic assisted microbial fuel cells: a review**. *Biomass Bioenergy* 2021, **148**:106028, https://doi.org/10.1016/j.biombioe.2021.106028

22. Howe CJ, Bombelli P: **Electricity production by photosynthetic microorganisms**. *Joule* 2020, **4**:2065-2069, https://doi.org/10.1016/j.joule.2020.09.003

23. Firoozabadi H, Mardanpour MM, Motamedian E: **A system-oriented strategy to enhance electron production of Synechocystis sp. PCC6803 in bio-photovoltaic devices: experimental and modeling insights**. *Sci Rep* 2021, **11**:12294, https://doi.org/10.1038/s41598-021-91906-9

24. McCormick AJ, Bombelli P, Scott AM, Philips AJ, Smith AG, Fisher AC, Howe CJ: **Photosynthetic biofilms in pure culture harness solar energy in a mediatorless bio-photovoltaic cell (BPV) system**. *Energy Environ Sci* 2011, **4**:4699-4709, https://doi.org/10.1039/C1EE01965A

25. Baikie TK, Wey LT, Lawrence JM, Medipally H, Reisner E, Nowaczyk MM, Friend RH, Howe CJ, Schnedermann C, Rao A, Zhang JZ: **Photosynthesis re-wired on the pico-second timescale**. *Nature* 2023, **615**:836-840, https://doi.org/10.1038/s41586-023-05763-9

26. • Tee JY, Ng FL, Keng FSL, Lee CW, Zhang B, Lin S, Phang SM: **Green synthesis of reduced graphene oxide by using tropical microalgae and its application in biophotovoltaic devices**. *Iscience* 2024, **27**:109564, https://doi.org/10.1016/j.isci.2024.109564.

In this paper, microalgae are employed to biosynthesize reduced graphene oxide (rGO), which was applied as anode materials for biophotovoltaic (BPV) devices. Compared to bare carbon paper anodes, the rGO-coated anodes demonstrate significant improvements in power density for BPV based on microalgae or cyanobacteria. These enhancements were attributed to the improved adhesion and contact of cells to rGO anode, as well as enhanced electrical conductivity due to oxygen group removal. This research highlights the potential of microalgal-derived materials in improving BPV devices for sustainable energy applications.

27. Nitnavare R, Bhattacharya J, Thongmee S, Ghosh S: **Photosynthetic microbes in nanobiotechnology: applications and perspectives**. *Sci Total Environ* 2022, **841**:156457, https://doi.org/10.1016/j.scitotenv.2022.156457

28. Shabnam N, Pardha-Saradhi P: **Photosynthetic electron transport system promotes synthesis of Au-nanoparticles**. *PLoS One* 2013, **8**:e71123, https://doi.org/10.1371/journal.pone.0071123

29. Beattie IR, Haverkamp RG: **Silver and gold nanoparticles in plants: sites for the reduction to metal**. *Metallomics* 2011, **3**:628-632, https://doi.org/10.1039/c1mt00044f

30. Rahman A, Kumar S, Bafana A, Dahoumane SA, Jeffryes C: **Biosynthetic conversion of Ag^{+} to highly stable Ag^{0} nanoparticles by wild type and cell wall deficient strains of *Chlamydomonas reinhardtii***. *Molecules* 2018, **24**:98, https://doi.org/10.3390/molecules24010098

31. •• Zhu X, Xu Z, Tang H, Nie L, Nie R, Wang R, Liu X, Huang X: **Photosynthesis-mediated intracellular biomineralization of gold nanoparticles inside chlorella cells towards hydrogen boosting under green light**. *Angew Chem Int Ed* 2023, **62**:e202308437, https://doi.org/10.1002/anie.202308437.

This study demonstrates the photosynthesis-mediated biosynthesis of gold nanoparticles (Au-NPs) in microalgae. HAuCl4 is reduced into Au-NPs with diameter ~20 nm around thylakoid membrane domain by electrons produced during light reactions. Furthermore, the Au-NPs inside microalgae enable hypoxic photosynthesis and electron transfer directly to hydrogenase, greatly enhancing hydrogen production by microalgae. This work shows the biosynthesis of Au-NPs and how these biogenic products can be utilized for energy production.

32. Pierre F, Judith H, Are O, *et al.*: **Global carbon budget 2020**. *Earth Syst Sci Data* 2020, **12**:3269-3340, https://doi.org/10.5194/essd-12-3269-2020

33. Oh JJ, Ammu S, Vriend VD, Kieffer, Kleiner FH, Balasubramanian S, Karana E, Masania K, Aubin-Tam ME: **Growth, distribution, and photosynthesis of *Chlamydomonas reinhardtii* in 3D hydrogels**. *Adv Mater* 2024, **36**:2305505, https://doi.org/10.1002/adma.202305505

34. Jang I, Park J, Son Y, Min J, Park W, Yi C: **Photosynthetic living building material: effect of the initial population of cyanobacteria on fixation of CO_2 and mechanical properties**. *Constr Build Mater* 2023, **396**:132218, https://doi.org/10.1016/j.conbuildmat.2023.132218

35. Jacobson TA, Kler JS, Hernke MT, Braun RK, Meyer KC, Funk WE: **Direct human health risks of increased atmospheric carbon dioxide**. *Nat Sustain* 2019, **2**:691-701, https://doi.org/10.1038/s41893-019-0323-1

36. Zeng Y, Xie R, Cao J, Chen Z, Fan Q, Liu B, Lian X, Huang H: **Simultaneous removal of multiple indoor-air pollutants using a combined process of electrostatic precipitation and catalytic decomposition**. *Chem Eng J* 2020, **388**:124219, https://doi.org/10.1016/j.cej.2020.124219

37. Brilli F, Fares S, Ghirardo A, Visser P, Calatayud V, Muñoz A, Annesi-Maesano I, Sebastiani F, Alivernini A, Varriale V, Menghini F: **Plants for sustainable improvement of indoor air quality**. *Trends Plant Sci* 2018, **23**:507-512, https://doi.org/10.1016/j.tplants.2018.03.004

38. Balasubramanian S, Yu K, Meyer AS, Karana E, Aubin-Tam ME: **Bioprinting of regenerative photosynthetic living materials**. *Adv Funct Mater* 2021, **31**:2011162, https://doi.org/10.1002/adfm.202011162

39. Kellersztein I, Tish D, Pederson J, Bechthold M, Daraio C: **Multifunctional biocomposite materials from *Chlorella vulgaris* microalgae**. *Adv Mater* 2024, **2024**:2413618, https://doi.org/10.1002/adma.202413618

40. Liu H, Yu S, Liu B, Xiang S, Jiang M, Yang F, Tan W, Zhou J, Xiao M, Li X, Richardson JJ, Lin W, Zhou J: **Space-efficient 3D microalgae farming with optimized resource utilization for regenerative food**. *Adv Mater* 2024, **36**:2401172, https://doi.org/10.1002/adma.202401172

41. Chua ST, Smith A, Murthy S, Murace M, Yang H, Kühl M, Cicuta P, Smith AG, Wangpraseurt D, Vignolini S: **Light management by algal aggregates in living photosynthetic hydrogels**. *Proc Natl Acad Sci* 2024, **121**:e2316206121, https://doi.org/10.1073/pnas.2316206121

42. • Dutto A, Kan A, Saraw Z, Maillard A, Zindel D, Studart AR: **Living porous ceramics for bacteria-regulated gas sensing and carbon capture**. *Adv Mater* 2024,2412555, https://doi.org/10.1002/adma.202412555.

This study demonstrates a living porous ceramic that can host various types of microorganisms inside, which can perform CO_2 capture or gas sensing. The CO_2 capture is endowed by photosynthetic cyanobacteria, while gas-sensing relies on engineered *E. coli* that detect toxic gases and convert them into scents detectable by humans. The hierarchical porous clay structure effectively supports bacterial growth, nutrient distribution, and mechanical stability. The innovative material highlights the potential of living ceramics for environmental applications, providing a promising approach for carbon capture and air purification.

43. Kumar P, Arora K, Chanana I, Kulshreshtha S, Thakur V, Choi KY: **Comparative study on conventional and microalgae-based air purifiers: paving the way for sustainable green spaces**. *J Environ Chem Eng* 2023, **11**:111046, https://doi.org/10.1016/j.jece.2023.111046

44. Worrell E, Price L, Martin N, Hendriks C, Meida LO: **Carbon dioxide emissions from the global cement industry**. *Annu Rev Energy Environ* 2001, **26**:303-329, https://doi.org/10.1146/annurev.energy.26.1.303

45. Sarayu K, Iyer NR, Murthy AR: **Exploration on the biotechnological aspect of the ureolytic bacteria for the production of the cementitious materials — a review**. *Appl Biochem Biotechnol* 2014, **172**:2308-2323, https://doi.org/10.1007/s12010-013-0686-0

46. Heveran CM, Williams SL, Qiu J, Artier J, Hubler MH, Cook SM, Cameron JC, Srubar WV: **Biomineralization and successive regeneration of engineered living building materials**. *Matter* 2020, **2**:481-494, https://doi.org/10.1016/j.matt.2019.11.016

47. Nanda S, Patra BR, Patel R, Bakos J, Dalai AK: **Innovations in applications and prospects of bioplastics and biopolymers: a review**. *Environ Chem Lett* 2022, **20**:379-395, https://doi.org/10.1007/s10311-021-01334-4

48. •• Yu K, Feng Z, Du H, Xin A, Lee KH, Li K, Su Y, Wang Q, Fang NX, Daraio C: **Photosynthesis-assisted remodeling of three-dimensional printed structures**. *Proc Natl Acad Sci* 2021, **118**:e2016524118, https://doi.org/10.1073/pnas.2016524118.

In this paper, by embedding chloroplasts into polymers, the glucose produced during photosynthesis enables additional cross-linking reactions within the polymer matrix, leading to light-triggered enhancements of mechanical property and crack sealing. This study demonstrates a novel method to achieve self-remodeling and self-healing living material with biological systems.

49. Kwak SY, Giraldo JP, Lew TTS, Wong MH, Liu P, Yang YJ, Koman VB, McGee MK, Olsen BD, Strano MS: **Polymethacrylamide and carbon composites that grow, strengthen, and self-repair using ambient carbon dioxide fixation**. *Adv Mater* 2018, **30**:1804037, https://doi.org/10.1002/adma.201804037

50. Neshat SA, Mohammadi M, Najafpour GD: **Photosynthesis assisted anaerobic digestion of cattle manure leachate in a hybrid bioreactor: an integrated system for enhanced wastewater treatment and methane production**. *Chem Eng J* 2017, **330**:616-624, https://doi.org/10.1016/j.cej.2017.08.001

51. Frigaard NU, Dahl C: **Sulfur metabolism in phototrophic sulfur bacteria**. *Adv Microb Physiol* 2008, **54**:103-200, https://doi.org/10.1016/S0065-2911(08)00002-7

52. Neshat SA, Mohammadi M, Najafpour GD: **Effect of illumination intensity on photosynthesis assisted anaerobic digestion of cattle manure leachate for enhanced biogas production**. *Chem Eng J* 2018, **338**:8-14, https://doi.org/10.1016/j.cej.2018.01.005

53. Antal TK, Lindblad P: **Production of H_2 by sulphur-deprived cells of the unicellular cyanobacteria Gloeocapsa alpicola and Synechocystis sp. PCC 6803 during dark incubation with methane or at various extracellular pH**. *J Appl Microbiol* 2005, **98**:114-120, https://doi.org/10.1111/j.1365-2672.2004.02431.x

54. • Elman T, Ho TTH, Milrad Y, Hippler M, Yacoby I: **Enhanced chloroplast-mitochondria crosstalk promotes ambient algal-H_2 production**. *Cell Rep Phys Sci* 2022, **3**:100828, https://doi.org/10.1016/j.xcrp.2022.100828.

The study demonstrates a mutation strain of green algae capable of sustained and scalable hydrogen production for a long period. This is due to enhanced energetic exchange between chloroplasts and mitochondria. This breakthrough offers a promising pathway for industrial-scale biohydrogen production.

55. Kosourov SN, Seibert M: **Hydrogen photoproduction by nutrient-deprived *Chlamydomonas reinhardtii* cells immobilized within thin alginate films under aerobic and anaerobic conditions**. *Biotechnol Bioeng* 2009, **102**:50-58, https://doi.org/10.1002/bit.22050

56. Laurinavichene TV, Fedorov AS, Ghirardi ML, Seibert M, Tsygankov AA: **Demonstration of sustained hydrogen photoproduction by immobilized, sulfur-deprived Chlamydomonas reinhardtii cells**. *Int J Hydrog Energy* 2006, **31**:659-667, https://doi.org/10.1016/j.ijhydene.2005.05.002

57. Kamshybayeva GK, Kossalbayev BD, Sadvakasova AK, Zayadan BK, Bozieva AM, Dunikov D, Alwasel S, Allakhverdiev SI: **Strategies and economic feasibilities in cyanobacterial hydrogen production**. *Int J Hydrog Energy* 2022, **47**:29661-29684, https://doi.org/10.1016/j.ijhydene.2022.06.277

58. Bhatt A, Khanchandani M, Rana MS, Prajapati SK: **Techno-economic analysis of microalgae cultivation for commercial sustainability: a state-of-the-art review**. *J Clean Prod* 2022, **370**:133456, https://doi.org/10.1016/j.jclepro.2022.133456

59. Grama SB, Liu Z, Li J: **Emerging trends in genetic engineering of microalgae for commercial applications**. *Mar Drugs* 2022, **20**:285, https://doi.org/10.3390/md20050285