

## Review article

# Artificial photosynthesis to overcome oxygen deprivation during respiratory disease crisis: A mini review

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## Abstract

Patients with respiratory diseases are primarily treated for their symptoms, with oxygen therapy as support. During the Coronavirus Disease 2019 (COVID-19) pandemic, oxygen concentrators were in high demand, and even afterward, many patients died due to a shortage of oxygen cylinders. This crisis prompted many entrepreneurs to establish oxygen plants, which required a large-scale setup. The articles included in this review were searched using Google Scholar, Scopus, and Web of Science using appropriate keywords. Here, we summarize the need for oxygen and how this need can be met through artificial photosynthesis. Using solar energy in the presence of a catalyst, water can be split into hydrogen and various organic products, resulting in oxygen production. The produced oxygen can be stored in oxygen cylinders and supplied to hospitals for patients in need. The difference between oxygen concentrators and artificial photosynthesis is that in the former, atmospheric oxygen is concentrated, and no new oxygen is produced, whereas in the latter, oxygen is produced from water, which is more useful. This mini review discusses artificial photosynthesis, the process, and the role of nanotechnology in enabling it.

**Keywords:** Artificial photosynthesis, carbon, nanotechnology, oxygen production, solar energy.

Evidence exists that in many places of the world during the Coronavirus Disease 2019 (COVID-19) pandemic, people faced an oxygen crisis, leading to the death of many individuals. The SARS-CoV-2 virus enters human cells via its spike protein, which binds to the angiotensin-converting enzyme 2 receptor, resulting in severe pneumonia and acute respiratory distress syndrome. Elderly individuals with cardiovascular disease are at a higher risk of developing severe COVID-19, whereas younger, healthier individuals are generally more resistant.<sup>(1)</sup> Among several other causes, microRNA has also been exploited as a possible palliative cure for COVID-19.<sup>(2)</sup> Similarly,

chronic obstructive pulmonary disease (COPD) is a serious respiratory condition that can be fatal. It results from lung damage, causing inflammation and airway obstruction that restricts airflow. Symptoms include breathing difficulties, a persistent mucus-producing cough, and wheezing. The two primary forms of COPD, emphysema and chronic bronchitis, often occur together and vary in severity among patients.<sup>(3)</sup> In many cases, fluid may accumulate near the lungs, causing pleural effusions. Pleural effusions, with unknown etiology, can cause complications in patients and may be detected with minimally invasive thoracoscopy.<sup>(4)</sup> Improving the quality of life of patients with COPD has been attempted through strength training.<sup>(5)</sup> The management of both diseases warrants symptomatic treatment, antibiotics, and antivirals, supported by intubation and continuous oxygen supply. Moreover, the high demand for oxygen during the pandemic posed a severe challenge for authorities to supply oxygen concentrators and generate oxygen quickly, leading in some cases to supply shortages.<sup>(6)</sup>

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This scenario highlights the death rate of patients<sup>(7)</sup> due to an oxygen crisis, prompting us to consider alternatives to producing oxygen other than via plant photosynthesis. Oxygen concentrators cannot produce oxygen; instead, they concentrate the oxygen already present in the air by removing nitrogen and providing it to patients.<sup>(8)</sup> Under such circumstances, artificial photosynthesis may realize its potential to produce oxygen and thus meet the oxygen demand during such a crisis.

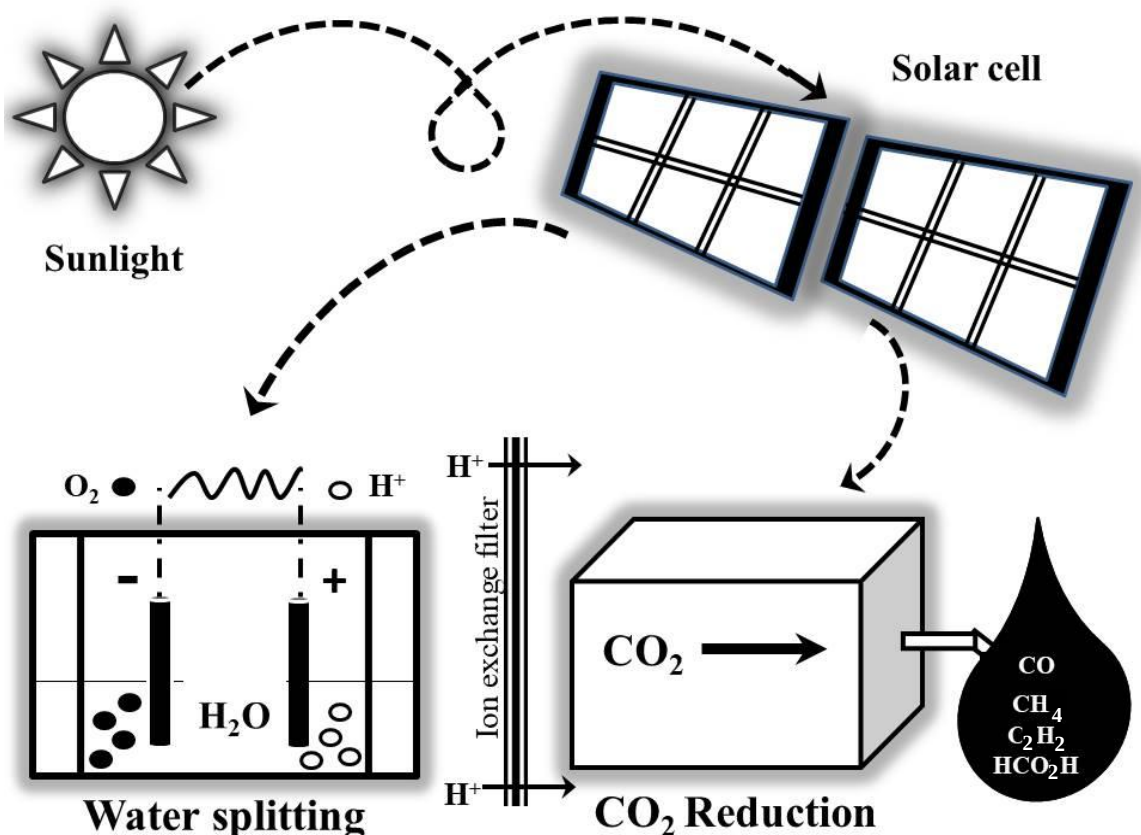
### Artificial photosynthesis

Artificial photosynthesis is a burgeoning research field that addresses humanity's challenges, including the need for sustainable energy sources and the mitigation of carbon emissions by replicating the chemical reactions of plants. The usual chemical process of photosynthesis converts sunlight, water, and CO<sub>2</sub> into oxygen and glucose via a pigment molecule called chlorophyll. In contrast, in artificial photosynthesis, high-energy electron splitting on catalyst surfaces produces carbohydrates and oxygen.<sup>(9)</sup> In an eco-friendly manner, this man-made methodology utilizes solar energy to produce useful chemical products, primarily hydrogen and other organic compounds. Furthermore, there is potential to develop new materials that can capture solar energy and catalyze the splitting of water molecules for chemical reactions that operate stably under specific conditions in an eco-friendly manner. Sometimes these solar cells specifically convert water into hydrogen and oxygen. Therefore, the oxygen produced can be stored in cylinders and supplied to the patients on demand.<sup>(10)</sup> An Italian scientist named Giacomo Ciamician introduced the knowledge of artificial photosynthesis.<sup>(11)</sup> He envisioned using photochemical devices to harness solar energy and transform it into storable solar fuel, utilizing conductors, catalysts, etc. Similarly, an important early innovation was achieved when Honda and Fujishima demonstrated that water could be split using ultraviolet (UV) light in the presence of TiO<sub>2</sub>.<sup>(12)</sup> In the 1980s, researchers advanced this concept by creating an artificial leaf that employed a thin-film amorphous silicon multi-junction sheet along with a TiO<sub>2</sub> catalyst to facilitate water splitting into hydrogen and oxygen.<sup>(13)</sup> Later, a polymer membrane was incorporated to transport protons, thereby marking one of the initial efforts to

develop a cost-effective silicon multi-junction cell-based device capable of functioning as an artificial leaf.<sup>(14)</sup> The growing demand for renewable energy in recent years has prompted researchers worldwide to explore the potential of artificial photosynthesis. Energy storage was the key distinction between photovoltaic cells and traditional photovoltaic cells. Photovoltaic cells in the solar panel operate via photosynthesis, while the other directly converts sunlight into electricity, depending on the climate conditions. However, in artificial photosynthesis, solar energy can be stored in semiconductors, which is a notable advantage compared to these two.<sup>(15)</sup>

### Key steps involved in artificial photosynthesis

An artificial photosynthesis system generally involves three key stages: light absorption and electron transfer, water splitting, and CO<sub>2</sub> conversion. Initially, photons in the 400–700 nm wavelength range are absorbed to provide the energy required for the following processes. During water splitting, the absorbed light excites electrons within the semiconductor, causing them to move to the catalyst's surface, where they facilitate the transition to hydrogen and oxygen. In the final step, CO<sub>2</sub> is reduced, thereby improving fuel quality.<sup>(16)</sup> Moreover, the emitted CO<sub>2</sub> can be subjected to cycloaddition to produce efficient fuels.<sup>(17, 18)</sup> Enhancing the efficiency of artificial photosynthesis requires materials with strong mechanical properties and cost-effectiveness. Typically, light is captured using photosensitive molecules or inorganic semiconductors. The incorporation of nanomaterials has substantially transformed artificial photosynthesis by enhancing light absorption and improving charge separation, thereby improving the overall efficiency. Recent advancements in photoelectrochemical cells have improved the productivity of converting solar energy into chemical energy, making them essential for generating solar fuels such as hydrogen. Similarly, researchers have made considerable advances in developing new, proficient catalysts, including biocatalysts and homogeneous and heterogeneous catalysts. These catalysts support the competence, progress, and selectivity of the reactions involved in artificial photosynthesis.<sup>(19)</sup> **Figure 1** depicts the photoelectrochemical water splitting technique used in artificial photosynthesis.



**Figure 1.** The photoelectrochemical water splitting technique is utilized in artificial photosynthesis.

### Catalysis in artificial photosynthesis

Catalysts play a crucial role in artificial photosynthesis. It is the primary source that transforms light, water, and  $CO_2$  into chemicals and fuels. There are two water splitting catalysts responsible for generating hydrogen and oxygen by splitting water molecules, namely the hydrogen evolution and oxygen evolution reactions.<sup>(20)</sup> Catalyst materials such as metal oxides, metal sulfides, and metal phosphides are traditionally used.<sup>(21)</sup> Additional usable materials, such as metal complexes, metal nanostructures, and metal-organic frameworks, are applicable for  $CO_2$  reduction. Some innovative fusion materials maintain stability throughout the operation and lend greater charge-transporting properties. However, every innovation has factors that limit its capability.<sup>(22)</sup> In artificial photosynthesis, metal complexes such as  $Mn_4Ca$  clusters serve as catalysts by imitating the functions of photosystems I and II that facilitate the oxidation and reduction of water. Utilizing high-valent metal-oxo intermediates for charge separation ultimately converts sunlight into chemical energy in the form of  $H_2$  and  $O_2$ .<sup>(23)</sup> Transition metal complexes are flexible and tunable, and are often utilized in homogeneous catalysis. Moreover, their durability and recyclability can be improved through heterogenization strategies,

as researchers have made notable advances in molecular catalysts for artificial photosynthesis. Researchers stated that the restrictions, such as the poor recyclability of traditional homogeneous catalysis, limit its industrial applications, which are being addressed by the recent advent of heterogenization processes. This process reduced the basic application costs and improved catalyst durability by immobilizing the catalysts on solid supports, thereby making them easily removable after reactions. Similarly, the immobilization of catalysts on nanomaterials, porous materials, nanostructured substrates, and metal-organic frameworks provides a more favorable environment for reactant access and enhances catalytic activity. Structural tunability, such as optimizing the electronic and steric properties of the catalyst, and durability, such as modifying or coating the catalyst with protective substances, improved the overall performance of artificial photosynthesis.<sup>(24)</sup> In addition, the essential properties such as high-temperature stability and single-atom functionality of catalysts in artificial photosynthesis contribute to improved  $CO_2$  photo-reduction efficiency. Zhang, *et al.* stated that the  $CuO/SiC$  catalyst exhibits exceptional performance in high-temperature semiconductor applications, demonstrating enhanced

activity above 150°C and achieving a solar energy conversion efficiency of 2.3% and a notable CO<sub>2</sub> conversion efficiency of 24.6%. The CuO/SiC catalyst yielded substantial amounts of CH<sub>4</sub> (2041.4 µmol/g), C<sub>2</sub>H<sub>4</sub> (15.2 µmol/g), and C<sub>2</sub>H<sub>6</sub> (63.6 µmol/g), thereby overcoming the limitations of industrial artificial photosynthesis. Furthermore, its high efficiency accelerated progress in photothermal catalysis, fostering further exploration of artificial photosynthesis for CO<sub>2</sub> and H<sub>2</sub>O conversion.<sup>(25)</sup> Advanced catalysts, such as Ag-supported NiO nanosheets, have demonstrated remarkable solar-to-chemical energy conversion efficiencies, thus highlighting their potential for large-scale artificial photosynthesis.<sup>(26)</sup> Similarly, bioinspired metal complexes offer exceptional stability and selectivity, playing a vital role in facilitating the multielectron and proton transfer processes that are essential for small molecule transformations.<sup>(27)</sup>

### Role of artificial photosynthesis catalysts or technologies in respiratory disease crises

Oxygen shortages during respiratory disease crises pose a considerable challenge to healthcare systems, particularly in intensive care units and remote areas.<sup>(28)</sup> Artificial photosynthesis represents an innovative step toward sustainable energy solutions that are inspired by nature's process of converting sunlight into chemical energy. During this period of rapid technological advancement, advanced catalysts have substantially improved the productivity and efficiency of artificial photosynthesis.<sup>(29)</sup> These catalysts play a crucial role in mimicking natural photosynthesis by converting sunlight, water, and CO<sub>2</sub> into valuable fuels and chemicals.<sup>(30)</sup> Emerging innovations in catalyst development have the potential to overcome current limitations, laying the foundation for cleaner energy production and contributing to the global effort to combat climate change.<sup>(31)</sup> Advanced technologies, such as photoelectrochemical cells and solar-driven water splitting, enable efficient oxygen production.<sup>(32)</sup> The integration of nanomaterials such as TiO<sub>2</sub><sup>(33)</sup>, graphene<sup>(34)</sup>, and carbon nanotubes enhances the reaction efficiency and stability.<sup>(35)</sup> Moreover, metal-based catalysts, including cobalt oxide (Co<sub>3</sub>O<sub>4</sub>)<sup>(36)</sup> and iron oxide (Fe<sub>2</sub>O<sub>3</sub>)<sup>(37)</sup>, play a vital role in facilitating the oxygen evolution reaction. The integration of these innovative catalysts has the potential to transform the energy landscape and promote progress toward advanced oxidation processes, as well as other sustainable and scalable approaches to address oxygen shortages in the medical sector, thereby ensuring a consistent supply for future patients in critical care

units.<sup>(38)</sup> **Table 1** describes the key catalysts/technologies used to address the respiratory disease crisis through artificial photosynthesis.

Photocatalytic water purification and related solar-driven catalytic systems present sustainable solutions; however, several practical challenges remain. One concern is the potential toxicity of catalyst residues, particularly when nanoparticles such as TiO<sub>2</sub> or ZnO are used. If poorly immobilized, these nanomaterials may leach into treated water, potentially posing ecotoxicological risks to aquatic organisms and affecting human health.<sup>(50, 51)</sup> Another challenge is water sourcing in arid regions, where freshwater scarcity limits the establishment of large-scale photocatalytic treatment systems. Regions with limited water infrastructure may struggle to supply sufficient feedwater, thus making the technology less feasible without integrated desalination or recycling systems.

In addition, variability in sunlight can influence the efficiency of solar photocatalytic processes. As catalysts such as TiO<sub>2</sub> rely on UV or visible light activation, fluctuations in cloud cover, seasonal variation, and geographic location can reduce reaction rates and treatment reliability.<sup>(52)</sup> Finally, safety considerations must be addressed when photocatalytic reactions generate gases. During water splitting, the simultaneous formation of hydrogen and oxygen can create explosive mixtures if not properly separated or ventilated, which requires careful reactor design and monitoring.<sup>(53)</sup> Therefore, while photoelectrocatalysis is a promising platform for oxygen production, addressing these technical, environmental, and safety concerns is essential for sustainable implementation.

### Conclusion

Artificial photosynthesis holds substantial promise for mitigating oxygen shortages during respiratory crises. By harnessing solar energy to drive water splitting reactions, this innovative technology can provide a sustainable and on demand oxygen supply. Moreover, artificial photosynthesis can be used to generate chemicals, biofuels, microbial biofuels, fertilizers, and biohydrogen that can be utilized in fields such as photoelectrochemical systems, enzyme manufacturing, agriculture, and environmental remediation. Similarly, artificial photosynthesis offers benefits such as enhanced stability and abundance, reduced environmental impact, and the ability to integrate into a wider network. Continued improvements in catalyst design and nanomaterial integration are essential to enhance the process's efficiency and scalability by overcoming current limitations.

**Table 1.** Key nanomaterials-based catalysts/technologies, utilized to improve oxygen shortage via artificial photosynthesis.

| S. No | Catalysts/ technology                      | Nanomaterials utilized                         | Other metals involved        | Mechanism                                                                   | Advantages                                                       | Potential application                                                            | Ref       |
|-------|--------------------------------------------|------------------------------------------------|------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------|----------------------------------------------------------------------------------|-----------|
| 1     | Photoelectrochemical (PEC) water splitting | Titanium dioxide (TiO <sub>2</sub> ), graphene | Fe, Co, Ni, Mo               | It uses light energy to split water into H <sub>2</sub> and O <sub>2</sub>  | Highly effective, scalable, renewable energy                     | Used for medical purposes to produce oxygen for ventilators and photodegradation | (39) (40) |
| 2     | Nanostructured metal oxides                | CuO, ZnO,                                      | Ni, Mn, Fe                   | It uses photocatalysis for water reduction                                  | Cost-effective and highly stable in water conditions             | Used for generating oxygen in critical care                                      | (41) (42) |
| 3     | Covalent organic frameworks (COFs)         | Porous polymeric materials                     | Zn, Co, Fe                   | Facilitates oxygen evolution by capturing CO <sub>2</sub>                   | Has high surface area and light weight                           | Enrich the oxygen and CO <sub>2</sub> filtration in hospitals                    | (43)      |
| 4     | Hybrid nanocomposites                      | Carbon nanotubes                               | Ni, Cu, Co, Fe               | Enhances charge separation for effective oxygen release                     | Has multifunctional properties and is highly stable              | Smart O <sub>2</sub> delivery systems                                            | (44)      |
| 5     | Metal organic frameworks (MOFs)            | Zeolite imidazole frameworks (ZIFs)            | Zn, Fe, Cu                   | Captures and converts CO <sub>2</sub> to release O <sub>2</sub>             | Has tunable properties with high porosity                        | Provides antimicrobial and protective properties                                 | (45)      |
| 6     | Artificial leaf technology                 | Carbon quantum dots, graphene                  | Cu, Ni, Co                   | Imitates natural photosynthesis for the direct production of O <sub>2</sub> | Used for long-term oxygen generation and sustainable             | Should be improved to use as an oxygen supply and personal respiratory support   | (46)      |
| 7     | Bioinspired enzymatic catalysis            | Enzyme immobilized nanostructures              | Fe, Cu, Mn                   | Imitates biological O <sub>2</sub> production pathways                      | Highly selective and biocompatible                               | Used as clinical respiratory devices and in oxygen therapy                       | (47)      |
| 8     | Plasmonic photocatalysis                   | Silver (Ag) and Gold (Au) nanoparticles        | Ag, Au                       | Increases light absorption for effective production of O <sub>2</sub>       | High light absorption with quick reaction rates                  | Used in air purification and oxygen supply in hospitals                          | (48)      |
| 9     | Photothermal catalysis                     | Silver-based nanostructures,                   | Ag, Cu, Ni, TiO <sub>2</sub> | It increases the O <sub>2</sub> evolution by utilizing light and heat       | It works at high temperatures and is suitable for industrial use | Large-scale oxygen supply for the medical sector                                 | (49)      |

### Author contributions

DJM, HRM, AG, and KG contributed substantially to the concept and design of this study, acquiring the data, reviewing the literature, and performing data analysis and interpretation. DJM, HRM, AG, and KG contributed substantially to acquiring the data. DJM, AG, and KG contributed to drafting the manuscript. AG and KG critically edited the manuscript for important intellectual content. All authors approved the final version submitted for publication and take responsibility for statements made in the published article.

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### Conflict of interest statement

All authors have completed and submitted the International Committee of Medical Journal Editors Uniform Disclosure Form for Potential Conflicts of Interest. All authors declare that they have no conflicts of interest.

### Data sharing statement

The present review is based on the references cited. All data generated or analyzed during the present study are included in this published article and the citations herein. Further details, opinions, and interpretation are available from the corresponding author on reasonable request.

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