

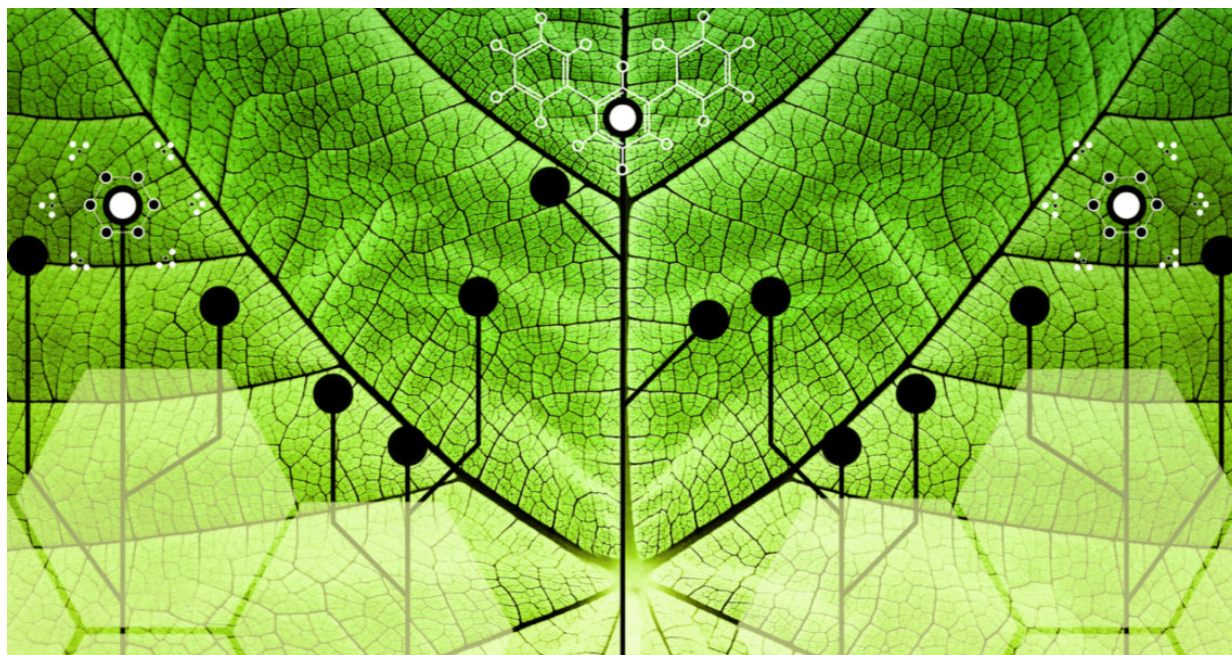
# Grao en Bioloxía

## Memoria do Traballo de Fin de Grao

**Energy production through artificial photosynthesis**

**Producción de enerxía a través de la fotosíntesis artificial**

**Produción de enerxía a través da fotosíntese artificial**



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# Summary

In this document, I analyze the current status of energy landscape and its mid-term implications on Earth and society, focusing on the need of transitioning to renewables, and emphasizing in artificial photosynthesis as a very interesting approach. Likewise, I review what has been done and researched in the field of artificial photosynthesis and how each stage of the natural photosynthesis has been mimicked; as well, what problems are faced and the solutions found to palliate them. I conclude this work pinpointing what is left to further investigate to finally achieve a viable, durable artificial system, capable of producing and storing chemical energy from water and carbon dioxide.

**KEYWORDS:** Artificial photosynthesis, solar energy, water-splitting, carbon dioxide.

En este documento, analizo el estado actual del panorama energético y sus implicaciones a medio plazo en la Tierra y en la sociedad, enfocándome en la necesidad de lograr la transición a las energías renovables. En este aspecto, haré especial hincapié en la fotosíntesis artificial, concluyendo que es una de las más prometedoras. Del mismo modo, reviso lo que se ha hecho e investigado en el campo de la fotosíntesis artificial; cómo se ha imitado cada parte de la fotosíntesis natural, a qué problemas se enfrenta y las soluciones encontradas para paliarlos. Finalizo el trabajo señalando qué queda por investigar para lograr un sistema fotosintético artificial viable y duradero, capaz de producir y almacenar energía química a partir de agua y dióxido de carbono.

**PALABRAS CLAVE:** Fotosíntesis artificial, energía solar, hidrólisis, dióxido de carbono.

Neste documento analizo o estado actual do panorama enerxético e as súas implicacións a medio prazo na Terra e na sociedade, centrándome na necesidade de lograr a transición ás enerxías renovables. Neste aspecto, conclúo que a fotosíntese artificial é unha das máis prometedoras. Do mesmo xeito, repaso o que se fixo e investigou no campo da fotosíntese artificial: como se imitou cada parte da fotosíntese natural, que problemas ten e as solucións atopadas para palialos. Finalizo o traballo sinalando que queda por investigar para finalmente acadar completamente un sistema fotosintético artificial viable e duradeiro, capaz de producir e almacenar enerxía química a partir de auga e dióxido de carbono.

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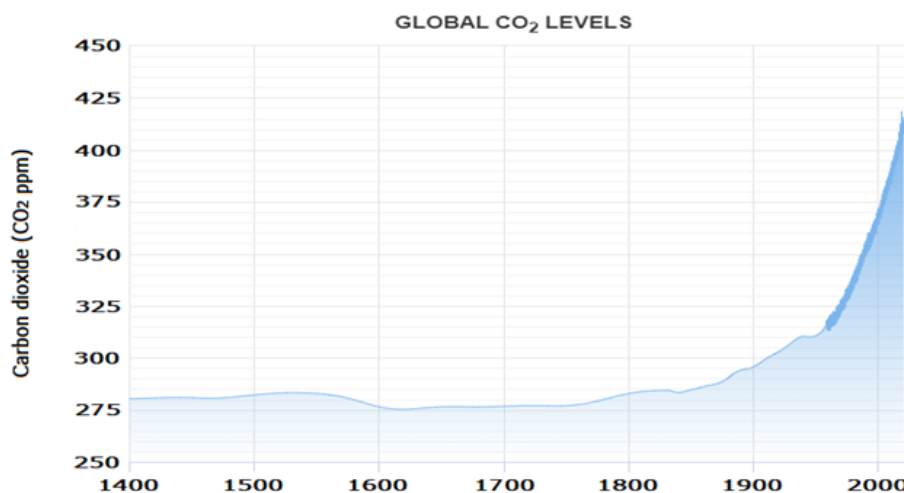




# 1. Introduction

## 1.1 CURRENT ENERGY LANDSCAPE

Driven by an urgent need to mitigate the effects of global warming and a foreseen end to the world's fossil fuel resources, an increasing tendency toward renewable energies is fostered by the international community. The increase in the concentration of CO<sub>2</sub> due to anthropogenic causes derives, through the greenhouse effect, in a significant increase in average global temperature. This means of temperature can cause serious problems in our society, and we can define a maximum permissible atmospheric CO<sub>2</sub> concentration that will limit the global temperature to a safe value for the development of humanity. There are numerous variables in the game and uncertainty both in the models that correlate the global average temperature with the concentration of atmospheric CO<sub>2</sub>, as in the average global temperature that is considered "safe". In an intermediate estimate (neither too conservative nor too aggressive), an atmospheric CO<sub>2</sub> concentration of 550 ppm, or +2 °C is the upper limit to prevent the triggering of several "worst" effects of global warming, such as the extreme desertification of habitable land and the retreat of coastline lines originated from the rise in sea level (Arnell, 2002). Recall that atmospheric CO<sub>2</sub> has increased dramatically from approximately 280 ppm in the 1700s to 415 parts per million (ppm) recently, as displayed in **Figure 1**.

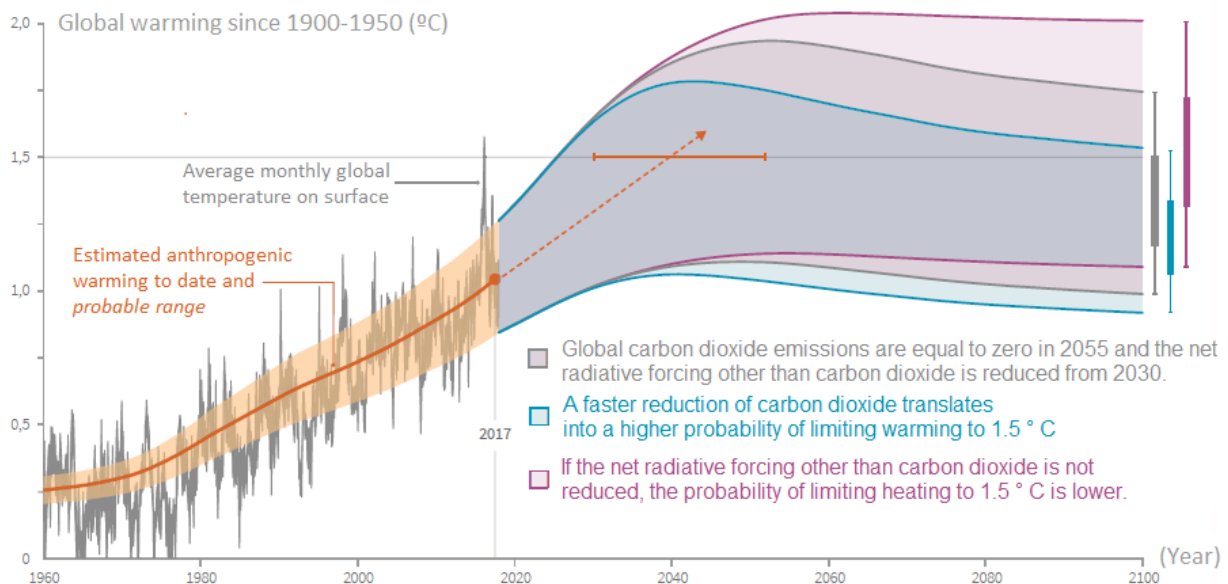


**Figure 1** | Evolution of the atmospheric concentration of CO<sub>2</sub> on earth based on data obtained from the Law Dome DE08, DE08-2, and DSS Ice Cores from Antarctica, analysed by the Carbon Dioxide Information Analysis Centre (CDIAC) (Etheridge *et al.*, 2010).

According to data from the latest Intergovernmental Panel on Climate Change (IPCC) inform (Masson-Delmotte *et al.*, 2018), it is estimated that human activities have caused a global warming of approximately 1.0 °C with respect to pre-industrial levels and global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate (assuming no changes in environmental policies). It is also important to take into account that anthropogenic emissions

from the pre-industrial period to the present are also accumulated, and they will increase global warming from centuries to thousands of years. In this regard, IPCC informs that global warming on a multi-decade time scale would be stopped if the net global anthropogenic CO<sub>2</sub> emissions were downed to zero and maintained at that rate and net radiative forcing other than CO<sub>2</sub> was reduced. In these conditions, the maximum temperature to be reached is determined by the net global anthropogenic CO<sub>2</sub> emissions and by the level of radiative forcing other than CO<sub>2</sub> (that is, (methane, nitrous oxide, water vapor and other greenhouse effect gases) accumulated until such time that the net CO<sub>2</sub> emissions are equal to zero. On longer time scales, to avoid further warming due to feedback from the Earth system and the reverse acidification of the oceans, it could be necessary a net negative global anthropogenic CO<sub>2</sub> emissions may and further reduce the radiative forcing other than CO<sub>2</sub>; both conditions will be necessary to reduce sea level rise.

IPCC also elaborated several models in 2018, as shown in **Figure 2**, that display predictions on how CO<sub>2</sub> emissions should be reduced to mitigate global warming, thus fixating some doable objectives to work on. In the trajectories of the models in which the warming does not exceed 1.5 °C or exceeds it in a minimal way, the net global anthropogenic CO<sub>2</sub> emissions decrease by approximately 45% by 2030 compared to 2010 levels, and are equal to zero around 2050. So that global warming does not exceed the limit of 2 °C, it is estimated that CO<sub>2</sub> emissions have to be reduced by approximately 25% by 2030 in most trajectories and be equal to zero around 2070. In non-CO<sub>2</sub> emissions of trajectories that will most probably limit global warming to 1.5 °C, drastic reductions are observed that are similar to those of trajectories that limit heating to 2 °C, meaning these emissions have to be reduced nevertheless.



**Figure 2** | Different theoretical scenarios of CO<sub>2</sub> emissions reduction. The different colors delimit areas of probable temperatures that will be reached according to different policies on CO<sub>2</sub> reduction, based on the recorded average monthly global temperatures on Earth’s surface. (Masson-Delmotte *et al.*, 2018).

For trajectories to limit global warming to 1.5 °C, rapid and powerful transitions in energy, land, urbanism, infrastructure systems, and industry would be required. Such transitions are

unprecedented in terms of scale, and imply profound reductions in emissions in all sectors, a broad set of mitigation options and a significant increase on the scale of investments in those fields.

As a final blow, demand for energy is estimated to increase at least twice by 2050 in relation to the present global consumption, due to a predicted increase on the population and economic growth. These alarming data show that the transition from non-renewable energies, emittant of large amounts of CO<sub>2</sub> to clean, carbon-neutral or carbon-negative energies should be our main priority nowadays and the focus of most of the research in the energy field.

At this point, I would like to put the focus on artificial photosynthesis. As one of the most interesting and promising areas of research on this regard, it being the only renewable source of energy known to date that directly removes CO<sub>2</sub> from atmosphere and, likewise, the only Negative Emissions Technology (NET) that produces energy directly at the same, as shown in **Table 1**. This technology would greatly help to achieve these milestones proposed during the last IPCC once it is deployed at large scale and in a profitable and efficient way. Being a form of solar energy (most specifically, a solar fuel-like source of energy), it benefits from the immense theoretical potential from sunlight. By means of artificial photosynthesis, this solar energy is transformed into chemical energy, and this transformation limits the extractable potential of the process.

**Table 1** | Resume of the Negative Emissions Technologies (NETs), which are the technological procedures that allow CO<sub>2</sub> extraction from the atmosphere (based on Herzog, 2009).

TECHNOLOGY OR TECHNIQUE	DESCRIPTION	CO <sub>2</sub> STORAGE MEDIUM
AFFORESTATION/REFORESTATION	The planting of trees to fix atmospheric carbon in biomass and soils	Soils/Vegetation
BIOCHAR	Converting biomass to biochar and using the biochar as a soil amendment	Soils
BIOENERGY WITH CO <sub>2</sub> CAPTURE AND STORAGE	Removal the CO <sub>2</sub> from the air by plants into biomass, combustion of the biomass to produce energy and CO <sub>2</sub> , which is captured	Deep Geologic Formations
DIRECT AIR CAPTURE	Removal of CO <sub>2</sub> from ambient air by engineered systems	Deep Geologic Formations
ENHANCED WEATHERING (MINERAL CARBONATION)	Enhancing the weathering of minerals, where CO <sub>2</sub> in the atmosphere reacts with silicate minerals to form carbonate rocks	Rocks
MODIFIED AGRICULTURAL PRACTICES	Adopting agricultural practices like no-till farming to increase carbon storage in soils	Soils
OCEAN (IRON) FERTILIZATION	Fertilizing the ocean to increase biological activity to pull carbon from the atmosphere into the ocean	Ocean
OCEAN ALKALINITY	Adding alkalinity to the oceans to pull carbon from the atmosphere via chemical reactions	Ocean
ARTIFICIAL PHOTOSYNTHESIS	The production of energy through a technological process that mimics natural photosynthesis performed by plants, using CO <sub>2</sub> , water and sunlight to produce chemical energy	Chemical compounds

## 1.2. POTENTIAL OF SOLAR ENERGY AND ARTIFICIAL PHOTOSYNTHESIS

Solar energy, which has a great potential as a clean, cheap, and sustainable energy source, is the most profitable amidst all the renewable sources of energy. According to NASA data (Lindsey, 2009), about 340 watts per square metre (W/m<sup>2</sup>) of energy strike the Earth's at the top of its

atmosphere on average, from which 29 % is reflected back and 23 % is absorbed in the atmosphere. This means only 48 % of this energy is absorbed in the surface. The theoretical potential of solar power is, then, the integral of this remaining energy flux over the earth's surface area ( $4\pi r^2$ , where r is earth's radius):

$$342.5 \text{ W/m}^2 \cdot 0.49 = 166.6 \text{ W/m}^2$$

$$P = (166.66 \text{ W/m}^2) \cdot (4\pi r^2) = (166.66 \text{ W/m}^2) \cdot (4\pi) \cdot (6,378 \text{ km})^2 (10^6 \text{ m}^2/\text{km}^2) \cdot (10^{-12} \text{ TW/W}) = 85,160 \text{ TW}$$

where "m" stands for metres, "km" stands for kilometres and "TW" is tera-watts. Extraction of this solar energy is achieved in three different ways as seen in **Table 2**: through solar electricity, where solar energy is converted first into electricity; through solar thermal energy, where solar energy is converted into mechanical energy and lastly through solar fuels which is an umbrella term that encompasses a collection of processes and where sunlight is directly converted into chemical energy (artificial photosynthesis falls within the latest category). Assuming that this conversion is performed through a photochemical route limited by modest temperatures and non-concentrated sunlight, the thermodynamic limit to the conversion efficiency to chemical fuel is approximately 68% (Nelson, 2003).

**Table 2.** Theoretical and extractable potential of the main renewable energy sources, based on the thermodynamic limit of conversion efficiencies calculated by Nelson (2003). In bold, the potential of solar energies (solar electricity, solar fuels and solar thermal energy), the most profitable among all renewable sources.

ENERGY RESOURCE	Theoretical Potential (TW)	Extractable Potential (TW)	Technical Potential (TW)
WIND	1,000	250	14
<b>SOLAR THERMAL</b>	<b>85,160</b>	<b>18,500</b>	<b>5,450</b>
<b>SOLAR FUELS</b>	<b>85,160</b>	<b>57,900</b>	<b>2,370</b>
<b>SOLAR ELECTRICITY</b>	<b>85,160</b>	<b>55,560</b>	<b>7,200</b>
OCEAN WAVE	34	8.5	0.62
OCEAN TIDAL	2.4	0.6	0.037
OCEAN THERMAL GRADIENT	3.9	0.033	0.0033
OCEAN SURFACE CURRENTS	8.1	2	0.012
OCEAN SALINITY GRADIENT	3	0.74	0.074
HYDROPOWER	12	3.5	1.2
GEO THERMAL	44	2.8	1.9

Assuming a theoretical potential of 85,160 TW, the extractable potential of the "equivalent chemical fuel" power is:

$$85,160 \text{ TW} \cdot 0.68 = 57,900 \text{ TW}.$$

We can foretell that, potentially, solar energy by itself, through any of these three routes, can cover the energetic requirements of humanity: we consumed around 20 TW globally in 2018, according to the International Energy Agency (IEA) data published in 2019. As established above, the mechanism that has a greater theoretical extractable potential of effectiveness (but not the greatest technical potential) is the production of fuels derived from solar energy. In nature, this is the way in which photosynthetic organisms take advantage of sunlight to grow, through mechanisms perfected during an extremely long process of evolutionary refinement (over 2.5 billion years), which is indicative of the appropriateness and effectivity of this solar energy exploitation maneuver. It is important, though, to spotlight that, by definition, the technical potential only considers the “demonstrated practices” that somehow already take into account profitability and energy returned energy invested (EROEI). We have the technology to build a platform in the middle of the Sahara to extract solar light, but that would be prohibitively expensive and not profitable at all. Still, the capacity of solar fuels to extract CO<sub>2</sub> from atmosphere, and the fact that the technical potential will not only but increase as more research is done and technology evolves, makes them the most promising energy source.

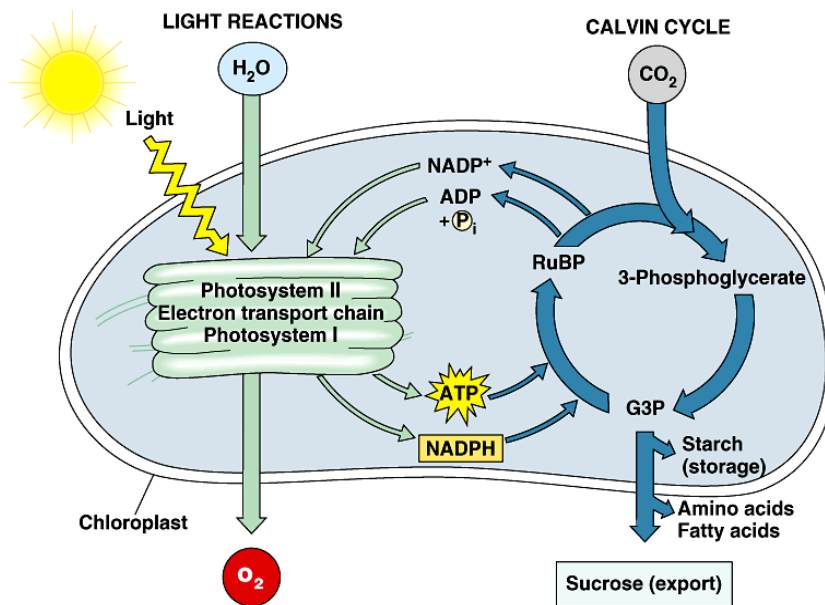
So, a singularly attractive approach is to just imitate nature and employ solar energy to form chemical bonds as plants do in natural photosynthesis, by means of artificial photosynthetic systems, capable of efficiently trap and convert solar energy into chemical energy, and to store it in the form of chemical bonds of solar fuels such as hydrogen or hydrogen peroxide, or reduced carbon species, while at the same time subtracting CO<sub>2</sub> from atmosphere and releasing oxygen. This new technology has the long-term potential to entirely transform society towards sustainability like no other, engineered alone or together with other technologies into all our structures (i.e., buildings, highways, vehicles). But, how to replicate photosynthesis?

### 1.3 NATURAL PHOTOSYNTHESIS

The first step to imitate plants is studying the natural process of photosynthesis in depth, and so has been done thoroughly for years and decades. As it is known, natural photosynthesis is the process by which sunlight and CO<sub>2</sub> is captured from the environment and converted into chemical energy, and more precisely, into the energy of chemical bonds of organic molecules that are the building blocks of all living organisms. It follows the formula:



where [CH<sub>2</sub>O] represents the produced organic molecules. To achieve this, water is split, breaking into oxygen and protons, as shown in **Figure 3**. The oxygen is then released, and it can be used later by other non-photosynthetic organisms to breathe. The protons, though, are processed and utilized in the posterior phases of photosynthesis. The following explanation of the photosynthesis, which is only a superficial overview on the different stages and components of it, is written under the guideline of the textbook “Campbell Biology” (Urry *et al.*, 2017), to ensure its veracity and trustworthiness.



**Figure 3** | Simplified scheme of the natural photosynthesis, where the absorption of light and splitting of water are related to the reduction of CO<sub>2</sub>, thus producing energy (Urry *et al.*, 2017).

Traditionally, photosynthesis has been divided into two main phases: the light-dependent reactions that produce adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) and the light independent reactions, also known as “Calvin-Benson-Bassham” (CBB) cycle, or Calvin cycle, which consist in the synthesis of organic compounds from CO<sub>2</sub>.

### 1.3.1 Light-dependent reactions

#### - Light absorption and charge separation

It starts with the absorption of sunlight by the photosynthetic pigments, such as chlorophyll *a*, chlorophyll *b* and carotenoids, which are found in the membranes of the thylakoids. These pigments are organized, along with some proteins, in complexes called photosystems. (**Table 3**).

**Table 3** | Main differences between Photosystem II (PSII) and Photosystem I (PSI). \*Names of the special pairs derive from the wavelength at which their absorb light; 680 and 700 nanometres (nm) respectively.

FEATURES/ PHOTOSYSTEM	PSII	PSI
SPECIAL PAIR	P680 (*)	P700 (*)
PRIMARY ACCEPTOR	Pheophytin	Chlorophyll <i>a</i>
ELECTRON DONOR	H <sub>2</sub> O	Plastocyanin

These photosystems contain about 300-400 molecules of pigments. When one of these molecules absorbs a photon, it goes into an excited state; that is, one of its electrons rises to an orbital of greater energy. Most of these excited pigments act together as an energy funnel, and pass the energy to other neighboring pigments through direct electromagnetic interactions, in a process called resonance energy transfer. In these transfers, the receptor molecule must not need more

energy to become excited than the donor, but less (that is, it can only absorb light of a longer wavelength). Together, the pigment molecules collect energy and transfer it to the central part of the photosystem II (PSII), called the reaction centre, where there is a single pair of chlorophyll *a* molecules, usually called the “special pair P680”. Once the energy reaches the special pair, it will no longer pass to other pigments by resonance energy transfer, but the special pair may lose an electron upon excitation and pass it to another molecule, called the primary electron acceptor, that is also within the reaction center. Accomplished this transfer, the electron will begin its journey through the Electron Transport Chain. This initial conversion of light energy into electrochemical potential that occurs in the reaction center of the PSII, has an estimated maximum thermodynamic efficiency of about 70 per cent. When the P680 of PSII absorbs energy and goes into an excited state (P680\*), it becomes a strong electron donor and can send the excited electron to the primary electron acceptor, a pheophytin (Pheo) molecule. These two (P680\* and Pheo) will function now as a radical pair state. This electron will then travel through the first section of the electron transport chain of photosynthesis, in a series of redox or electron transfer reactions.

- *Water-splitting*

After the special pair donates its excited electron, it has a positive charge and needs another electron to reestablish its normal state. This electron is obtained by the splitting of water molecules, a process that takes place in a part of the PSII called the “water oxidizing centre” (WOC) (the positively charged, high redox potential P680\* can only extract electrons from the water because it is highly oxidized). The water-splitting occurs as follows: first, two H<sub>2</sub>O molecules are merged together, from where four electrons are extracted; in this way, it can thus release four H<sup>+</sup> ions and produce one O<sub>2</sub> molecule. The efficiency of this reaction is high, being almost 55 % when driven by the energy of ‘red’ photons, but decreases to about 20 % when taking into account the fact that light is absorbed across the whole solar spectrum. About 10% of this oxygen produced is used by mitochondria in the leaf, to perform oxidative phosphorylation. The rest of the oxygen escapes into the atmosphere, where aerobic organisms use it to perform cellular respiration (Bolton & Hall, 1991).

- *Electron transport chain*

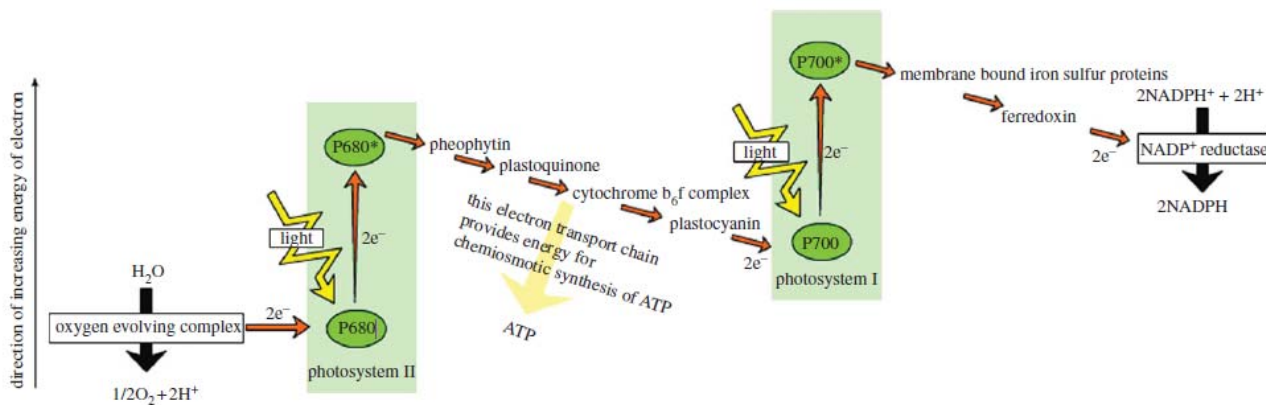
Once the hydrolysis has taken place, electrons can leave the PSII and continue on their way to the photosystem I (PSI), although not before being passed through a series of intermediaries, which are responsible for their transport and the generation of a gradient. When an electron leaves PSII, in charge of the pheophytin, it is firstly donated to a small organic molecule, the plastoquinone (Q), which reduces into plastoquinol (QH<sub>2</sub>). As a note, this reaction can only proceed continuously when the QH<sub>2</sub> molecules are oxidized (when they pass their just-gained electron, thus allowing it to be transferred to the NADP<sup>+</sup> and then to CO<sub>2</sub>), and this process can only happen when a new light photon is absorbed in PSI. Because of this saturation effect, the quantum efficiency of photosynthetic water splitting is again decreased. QH<sub>2</sub> will then transfer the electrons to the cytochrome b6f enzymatic complex (Cyt b6f) and, finally, to a copper-containing protein called plastocyanine (PC). As the electron circulates through this transport chain, it jumps from higher



levels of energy to lower ones, and so releases energy. Some of this energy is used to pump  $H^+$  protons from the stroma (outside the thylakoids) into the thylakoid lumen. This transference of  $H^+$ , in conjunction with the release of  $H^+$  from the water-splitting, forms a proton gradient that will be used to produce ATP (as it will be explained soon).

Once the electrons have passed through all these intermediaries, they reach the PSI, where they join the other special chlorophyll pair, called "P700". Since electrons have lost energy prior reaching the PSI, they must receive more energy, and so is accomplished by absorbing a new photon. The excited P700 is, as well, a strong electron donor and sends its electrons to its primary acceptor, this time a chlorophyll *a* molecule, initiating another electron transport chain, although this one is shorter. In this sequence of reactions, the electrons first pass to a series of membrane-bound iron sulfur ( $F_X$ ,  $F_A$  and  $F_B$ ) and then to a soluble ferredoxin ( $F_D$ ), from where are then finally transferred to an enzyme called  $NADP^+$  reductase, which passes the electrons to the reduced nicotinamide adenosine dinucleotide phosphate ( $NADP^+$ ) transporter molecule to create NADPH. NADPH finally travels to the Calvin cycle, where it is used to synthesize sugars from carbon dioxide.

The other necessary ingredient for the Calvin cycle is ATP, which is also provided by the light-dependent reactions. As it was earlier explained,  $H^+$  ions accumulate inside the thylakoid lumen and origin a concentration gradient. Protons tend to spread in favor of the gradient back to the stroma, and their only pathway is the enzyme ATP synthase. This enzyme takes advantage of the proton flow to form ATP from adenosine diphosphate (ADP) and phosphate ( $P_i$ ) in a process called chemiosmosis.



**Figure 4** | General scheme of the light-dependent reactions of photosynthesis, where P680 of PSII absorbs light and splits water, extracting electrons and sending them through an electron transport chain (PQ, Cyt  $b_6/f$  and PC) that takes them to the PSI. P700 absorbs light again and finally sends the electrons through another transport chain ( $F_X$ ,  $F_A$ ,  $F_B$  and then  $F_D$ ) to the  $NADP^+$  reductase to synthesize NADPH. This electron transport also causes a concentration gradient of protons from the lumen of the thylakoids to the stroma; ATP-synthase benefits from this and produces ATP (Wikipedia, 2005).

### 1.3.2 Light-independent reactions

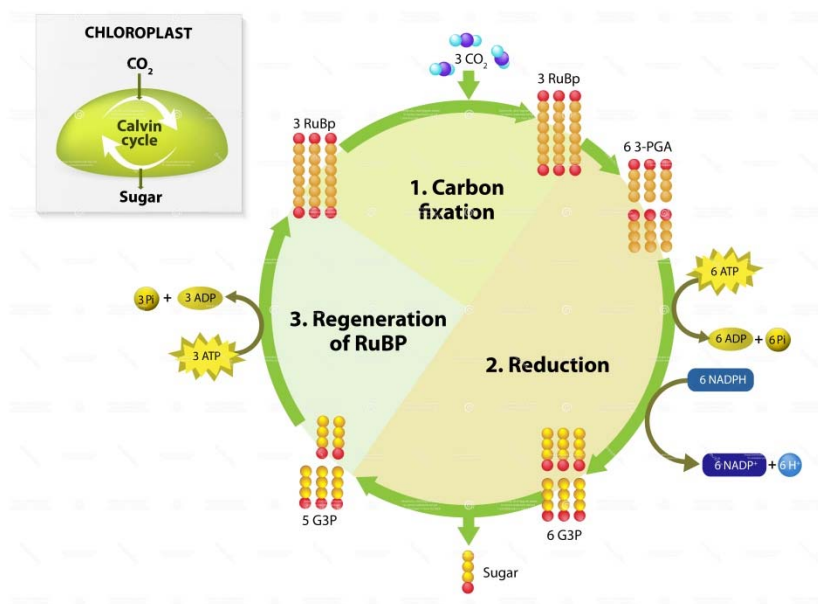
Once the ATP and the NADPH have been successfully gathered from the light-dependent reactions of the photosynthesis, they can be used to fixate and reduce the atmospheric  $CO_2$  into simple



organic molecules and to regenerate the structures needed to do so. This multi-step process is called CBB cycle, and it englobes the light-independent reactions of photosynthesis.

In plants, carbon dioxide enters the leaves through pores, called stomata, and diffuses into the stroma of the chloroplast, the site at which the reactions of the CBB cycle occur. These reactions are also called independent reactions of light, because light does not cause them directly. The carbon atoms of CO<sub>2</sub> molecules are fixated and used to form three-carbon sugars, in a process stimulated by the ATP and NADPH that come from the light reactions, and which depends on them. Unlike the light-dependent reactions, which occur in the thylakoid membrane, the Calvin cycle reactions occur in the stroma (inner space of the chloroplasts).

The reactions of the Calvin cycle can be divided into three main stages: carbon fixation stage, reduction stage and regeneration of the initial molecules stage, as it is represented in **Figure 5**.



**Figure 5** | Schematic representation of the three main stages of the CBB cycle, which occur in the stroma of chloroplasts. CO<sub>2</sub> enters the cycle so it can be reduced into sugars (Dreamstime photo stock).

- *Carbon fixation stage*

In the first step of the cycle, an enzyme nicknamed RUBISCO (RuBP carboxylase-oxygenase) catalyses the fixation of one CO<sub>2</sub> molecule to a five-carbon sugar, called ribulose bisphosphate (RuBP). However, the resulting 6-carbon molecule is unstable and quickly splits into two molecules of a three-carbon compound called 3-phosphoglycerate (3-PGA). Thus, for every CO<sub>2</sub> unit that enters the cycle, two 3-PGA molecules are produced.

- *Reduction of RuBP stage*

The Calvin cycle reduction stage, which requires ATP and NADPH, converts 3-PGA (from the fixation phase) into a three-carbon sugar. This process occurs in two main steps: First, each 3-PGA

molecule receives a phosphate group from ATP and becomes a twice phosphorylated molecule called 1,3-bisphosphoglycerate (1,3BPG), leaving ADP as a by-product. Secondly, 1,3BPG molecules are reduced. Each molecule receives two electrons from NADPH and loses one from their phosphate groups to become a triose, called glyceraldehyde 3-phosphate (G3P). This step produces NADP<sup>+</sup> and phosphate (P<sub>i</sub>) as by-products.

It is worth mentioning that the chemical energy of ATP and the reducing power of NADPH used in these steps, which are products of light-dependent reactions, keep the CBB cycle running. Reciprocally, the CBB cycle generates ADP and NADP<sup>+</sup>, which provides the necessary substrates for light-dependent reactions.

- *Regeneration stage*

Only some of the G3P molecules just synthesized leave the cycle to form glucose; the retaining must be recycled to regenerate the RuBP acceptor of carbon. This regeneration only takes place by requiring, again, ATP, and involves a complex series of reactions that I am not including here, for the sake of keeping this resume of the photosynthesis brief and introductory to the next segments.

The success of this complex process to generate and store energy derives from the fact that the raw materials and power needed for the synthesis of these chemical compounds are available in almost unlimited amounts in nature; sunlight, water and CO<sub>2</sub>. The efficiency of this process can be estimated, although several factors must be taken into account: The efficiency of the energy conversion from photons to glucose, assuming that only “red” photons are absorbed in the photosystems, is at about 30 % (Bolton, 1991). This impressive number is actually decreased by several means: chlorophyll does not just absorb “red” photons, but also more energetic photons, which have to be degraded to shorter wavelengths. Efficiency is also decreased by the saturation processes above mentioned and more significantly, in driving the enormous number of reactions that occur in photosynthetic organisms to maintain their organization, metabolism, reproduction and survival. Taking these various factors into account, the estimated maximum efficiency of photosynthesis is about 4.5 %; value which is rarely reached. Yield dry matter will only exceed 1 or 2 % in niche, specific cases, such as with the intense growing of sugar cane or with the in-laboratory culturing of algae. Normal values are just under 1 % (Blankenship *et al.*, 2011).

That low efficiency is the first drawback of photosynthesis as a medium to obtain energy. Other inconveniences are the lack of understanding of the structures that shape the photosynthetic machinery, the scalability and longevity that would make the artificial photosynthesis viable, as the plants have developed self-repairing machinery that we do not have yet, and the elevated cost of the investigation. First of all, we should get a clearer understanding of the functioning of photosynthetic machinery, through the elucidation of the molecular structures revolving around the process. Literature on this topic focuses on the elucidation of the functioning of PSI and PSII and intermediate catalysts.

## 2. Objectives

The objectives this document aims to accomplish are the following:

- To clarify why is important to progress on the topic of climatic situation and its problems regarding CO<sub>2</sub> atmospheric content, the foreseen end to the World's fossil fuel resources and renewable energy transition.
- To emphasize on how artificial photosynthesis is the one of the most appropriate and promising long-term solution for these issues.
- To sum up what has been done and researched and what is left to be achieved to try to overcome the challenges that such a wide and recent field of investigation come upon with, which are the following:
  1. More in-deep elucidation of molecular and supramolecular structures involved in the photosynthetic process, so as to achieve a clearer understanding of the functioning of photosynthetic machinery.
  2. Augment and improvement of the scalability and longevity of the artificial photosynthetic devices, including the incorporation of self-assembling and self-repairing mechanisms.
  3. Low efficiency of the solar-to-chemical energy conversion.
  4. Deployment of a fully operational, efficient and profitable artificial photosynthetic system to mass-produce energy and relieves the CO<sub>2</sub> atmospheric content.

## 3. Materials and methods.

In this section, I describe the procedure I have followed to find the articles I considered insightful, necessary and appropriate to obtain the desired results of my work. Due to the purely bibliographic nature of this document, no technical procedures, laboratory practices or detailed experimentation is described nor was it used in its elaboration.

I accessed Scopus and utilized it as the main source of bibliography for this manuscript. Using the "search" tab of the website, with keywords such as "artificial photosynthesis" "water-splitting", I was presented a plethora of scientific articles, which were then filtered and sorted according to relevance, date of publication, or simply by an extensive reading and checking of the most *a priori* promising ones. Some, though, were discarded, as they not contained the information I was

seeking (which is described in **Objectives**), although useful articles were already downloaded at this point of the time. From the references used in some of these I, as well, found other interesting manuscripts. This thorough search started in April, 2017 and finalized in October, 2019.

Direct Google search was used too, using the same search criteria as in Scopus, and from there, I was redirected to other online libraries and services that also were of utility, from which I can pinpoint Science Direct, Online Library Wiley and Research Gate.

To access one particular article (“Molecular Structure Elucidation with Charge-State Control”) I e-mailed Professor Diego Peña, from the University of Santiago de Compostela, USC, as he was one of the co-authors. He readily sent me a copy of it, which was used to elaborate some of the results of this document.

## 4. Results and discussion.

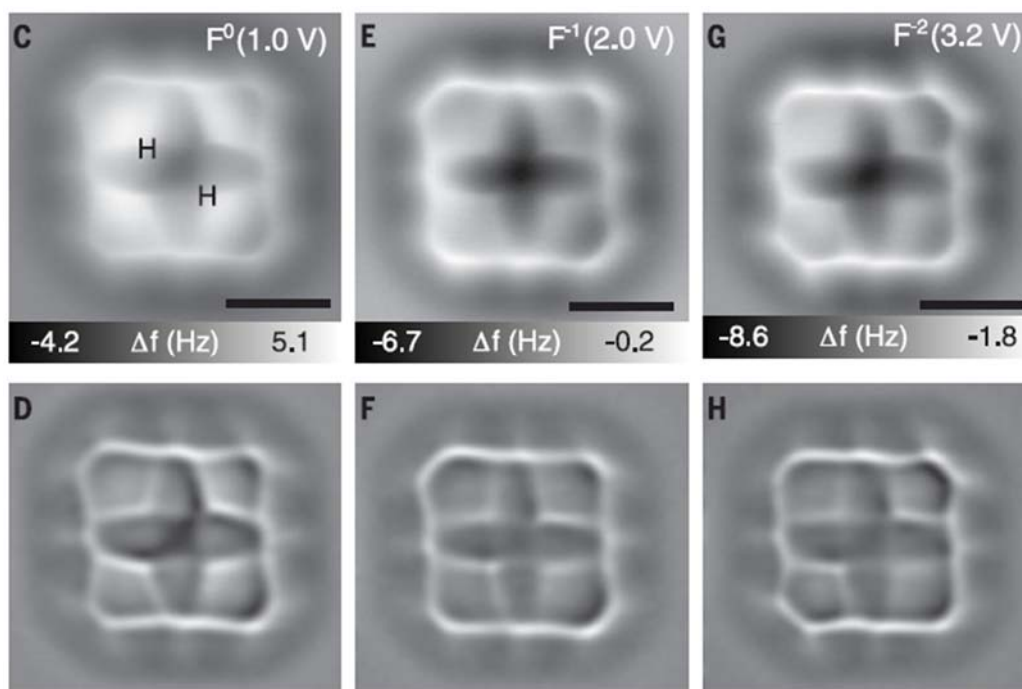
The results obtained can be classified according to the following categories: basic research on natural photosynthesis, based on the elucidation of the molecular structure of the components involved in the process; advances on improving the scalability and longevity of artificial photosynthetic systems and finally, attempts to replicate photosynthesis, through more or less functional devices, of different efficiencies and based on photolysis, the Calvin cycle, or both at the same time.

### 4.1 ELUCIDATION OF INVOLVED STRUCTURES

Regarding advances dedicated to the elucidation of the components involved in natural photosynthesis, I highlight the following works: the work of Zapletal and Herman (2014), dedicated to the study of the optical properties of the antenna II complex, that reveals details of the structure of the aforementioned complex, which help explain and understand the factors that affect the efficiency of the first part of photosynthesis, a fundamental factor for future, more profitable artificial devices.

Likewise, the work of Zedler *et al.* (2019), focused on the mechanism of photoreduction of photosynthetic intermediates similar to the NAD, opens the way for in situ spectrum electrochemical analysis for the study of the properties of the excited state of reactive intermediates in photocatalytic cycles, which is of vital importance to facilitate the photolysis of water in future artificial photosynthetic devices, because these mechanisms are very difficult to study and require delicate techniques, as described by them, due to the rattling short life of these intermediaries. Finally, I highlight another interesting work on elucidation of molecular structures;

the work of Peña, from the University of Santiago de Compostela, and his colleagues (Fatayer *et al.*, 2019). In their study, they isolate small organic molecules in multilayer films of sodium chloride, and control their charge status, thus solving their atomic structure in a neutral, cationic, anionic and dianionic state with atomic force microscopy. This is depicted in **Figure 6**.



**Figure 6** | Atomic force microscopy (AFM) images of porphine different charge states. C, D, neutral state ( $F^0$ ); E, F, anionic state ( $F^{-1}$ ) and G, H, dianionic state ( $F^{-2}$ ). Fatayer *et al.*, 2019.

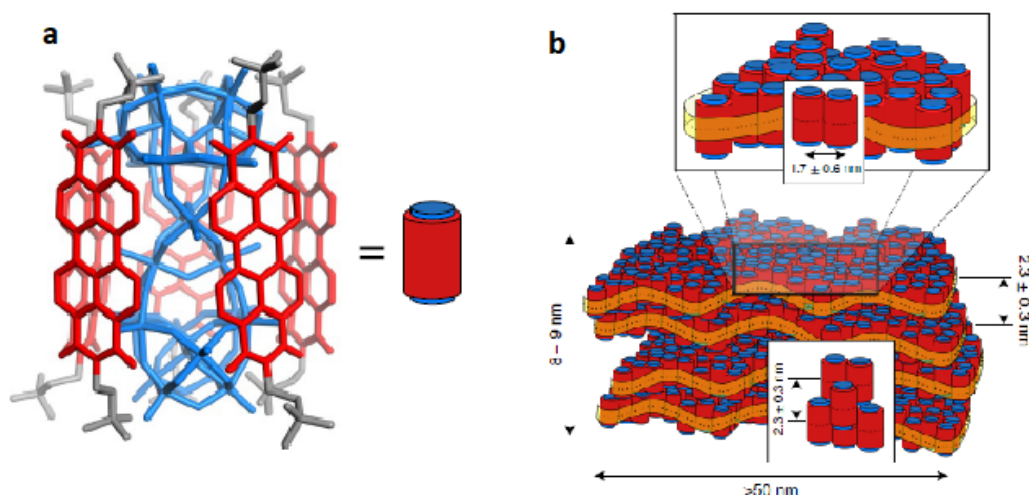
“The charge state of a molecule governs its physicochemical properties, such as conformation, reactivity, and aromaticity, with implications for on-surface synthesis, catalysis, photoconversion and applications in molecular electronics”. “We detected changes in conformation, adsorption geometry, and bond-order relations for azobenzene, tetracyanoquinodimethane, and pentacene in multiple charge states. Moreover, for porphine, we investigate the charge state–dependent change of aromaticity and conjugation pathway in the macrocycle. This work opens the way to studying chemical structural changes of individual molecules for a wide range of charge states”. His work clears up the way to the study of the chemical structure of small organic molecules, which will be of great help for the study of the components involved in photosynthesis.

Following the previous, and other similar works, which try to pave the way for the study of the molecular functioning of the structures involved in the process, it falls by its own weight the necessity to study the supramolecular structures that they carry out or that serve as support for photosynthetic processes themselves. This is not new; it has been the main focus of research in photosynthesis during the last decades, but it has not ceased to be important and necessary. The recent work of Capretti *et al.* (2019), details the functioning of photosynthetic membranes in thylakoidal grana and their interaction with sunlight like never before, highlighting how the placement and density of the structures collected in them changes upon variation in sunlight intensity. Their results indicate that “the relative contributions of light scattering and absorption

to the overall optical response of grana strongly depend on the concentration of the light-harvesting complexes.” Also that “for the pigment concentrations typically found in chloroplasts, the two mechanisms have comparable strengths, and their relative value can be tuned by variations in the protein composition or in the granal diameter”. Furthermore, they find that “collective modes in ensembles of grana significantly increase light absorption at selected wavelengths, even in the presence of moderate biological disorder. Small variations in the granal separation or a large disorder can dismantle this collective response”, from where they extract that “chloroplasts use this mechanism as a strategy against dangerously high illumination conditions, triggering a transition to low-absorbing states”, and conclude: “the morphological separation of the thylakoid membrane in higher plants supports strong nanophotonic effects, which may be used by chloroplasts to regulate light absorption”.

#### 4.2 SCALABILITY AND LONGEVITY

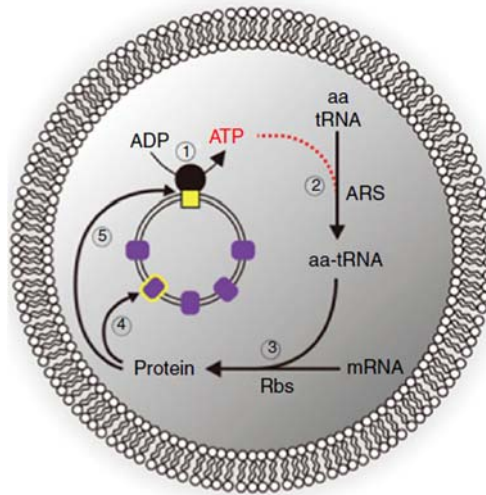
The previous study not only reveals information of great interest on the functioning of thylakoids, but also sheds light on a characteristic of them of great importance in the manufacture of systems that would replicate photosynthesis, and this is the self-organization of their components depending on the physicochemical conditions of the environment in which they are found. In the words of the investigators: “This adaptive self-organization capability is of interest as a model for novel bioinspired optical materials for artificial photosynthesis”. Systems that are designed must, with almost total security, be able, to a greater or lesser extent, to self-repair and self-organize, as is the case in natural photosynthesis, so that they are long-lasting and profitable. Bonchio *et al.* (2019) realized this, and in their work they designed chromophore molecules that are prepared to work with photolytic catalysts and with the ability to self-assemble, highlighting the importance of this characteristic in future inventions. In their words: “Here we report the self-assembly of multi-*p*-erylene-bisimide chromophores (PBI) shaped to function by interaction with a polyoxometalate water-oxidation catalyst ( $\text{Ru}_4\text{POM}$ ). The resulting  $[\text{PBI}]_5\text{Ru}_4\text{POM}$  complex shows a robust amphiphilic structure and dynamic aggregation into large two-dimensional paracrystalline domains, a redshifted light-harvesting efficiency of > 40 % and favourable exciton accumulation, with a peak quantum efficiency using 'green' photons ( $\lambda > 500 \text{ nm}$ ). The modularity of the building blocks and the simplicity of the non-covalent chemistry offer opportunities for innovation in artificial photosynthesis.” Their aggregates are shown in **Figure 7**.



**Figure 7** | Hierarchical organization of  $\{[PBI]_5Ru_4POM\}_n$  photosynthetic aggregates. a, Figurative representation of the  $[PBI]_5Ru_4POM$  building block (PBI shell, red cylinder;  $Ru_4POM$ , blue cylinder) and b, Multiscale model representation of cylinders packed into stacked nano-lamellae, with a mean molecular out-of-plane distance of  $(2.3 \pm 0.3)$  nm. The enlarged view shows a single lamellar plane, built from parallel alignment of the cylinders with a mean in-plane distance of  $(1.7 \pm 0.6)$  nm (Bonchio *et al.*, 2019).

In addition to being self-repairing, the materials involved must be robust, and resist unaltered for as long as possible, under the conditions of great oxidative stress that are produced by necessity to hydrolyse water. The work of Andrei *et al.* on “scalable triple cation mixed halide perovskite –  $BiVO_4$  tandems” (2019), in which they created, I quote here: “Scalable, bias-free solar water splitting tandem devices with an excellent stability of up to 20 h and a bias-free solar-to-hydrogen efficiency of  $0.35 \pm 0.14$  % . The high reliability of the fabrication procedures allows scaling of the devices up to  $10\text{ cm}^2$ ” provides valuable information on materials that may be necessary to be incorporated into the solar power production chain. In their words: “Such photoelectrode tandem systems are particularly interesting for the field of solar fuels, where one of the main aims is driving electrochemical processes (e.g., water splitting or  $CO_2$  reduction) without applying an additional electrochemical bias. The end goal for those photoelectrochemical systems is the broad implementation of lightweight monolithic (i.e., wireless) devices, which are also known as artificial leaves”. The application of components such as this will help prolong the life of chemical producing devices that will be used in the future to produce clean energy and remove  $CO_2$  from the atmosphere. In this I also highlight the work of Berhanu, Ueda and Kuruma (2019), who have managed to create an acellular system that synthesizes proteins and that obtains ATP to function through sunlight, thanks to a bacteriorhodopsin coupled to an ATP synthase, both being encapsulated in a proteolysosome; it is represented in **Figure 8**. This machinery is capable of producing its constituent elements *de novo*, making it self-sufficient and independent. The main drawback of this system is that free phosphates are accumulated, which may be detrimental for the stability of the molecules, but this problem is fixed with the brilliant addition of a phosphate recycling system, which ended up being of promising application for future cell-free devices.





**Figure 8** | Schematics of self-constituting protein synthesis in artificial photosynthetic cells. The numbers indicate the order of reactions; ①: adenosine triphosphate (ATP) synthesis, ②: aminoacylation of transfer RNA (tRNA) by aminoacyl-tRNA synthetase (ARS), ③: translation by ribosomes (Rbs), ④: de novo bacteriorhodopsin (bR) synthesis, and ⑤: de novo  $F_0$  synthesis (Berhanu *et al.*, 2019).

To cite them, “the current cell-free system is using creatine phosphate as a primary energy source; however, since this is unidirectional reaction, free phosphates accumulate in the system as the reaction goes on. Our artificial organelle can avoid this problem by recharge the free phosphate onto ADP after the ATP consumption.”

Thus, we see that numerous advancements and solutions have been achieved, and that these can be applied directly into the manufacture of artificial photosynthetic devices that are being designed today, and in the last years. Their successful (or not) incorporation will mean that these devices become better and better, until the day they become definitely profitable. As to now, I present here a compilation of the most outstanding systems created to date.

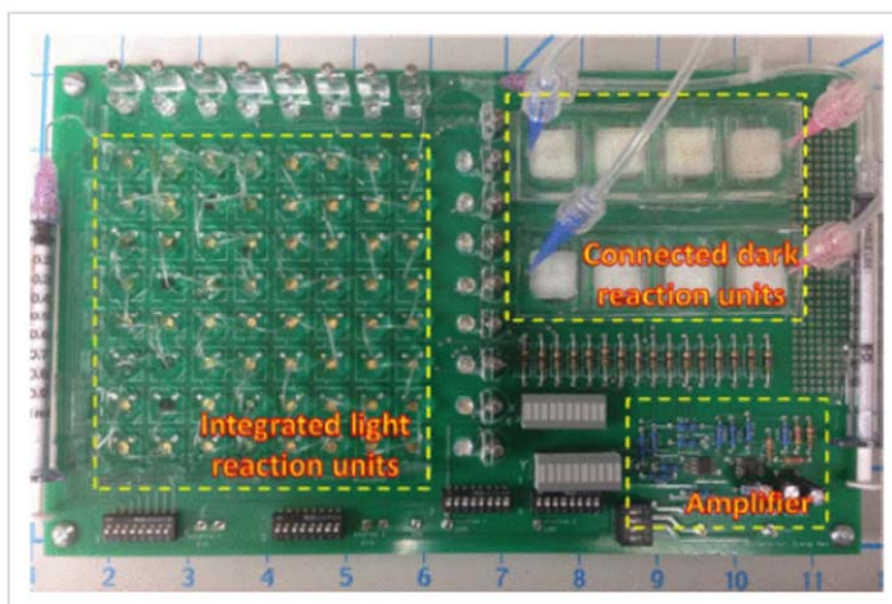
#### 4.3 ARTIFICIAL PHOTOSYNTHESIS: FUNCTIONAL DEVICES

As a first effective and promising device, I highlight the one developed by Wendel, Todd and Montemagno in 2010, which was a breakthrough in the field of artificial photosynthesis. They managed to develop a semi-artificial system that used the surfactant protein found in the foam of the frog *Physalaemus pustulosus* (Túngara frog) to transform solar energy into chemical energy with very high efficiency. “We present a cell-free artificial photosynthesis platform that couples the requisite enzymes of the Calvin cycle with a nanoscale photophosphorylation system engineered into a foam architecture using the Túngara frog surfactant protein Ranaspumin-2. This unique protein surfactant allowed lipid vesicles and coupled enzyme activity to be concentrated to the microscale Plateau channels of the foam, directing photoderived chemical energy to the singular purpose of carbon fixation and sugar synthesis, with chemical conversion efficiencies approaching 96%”. This system, although highly efficient, presents the inconvenience that it is not self-repairing nor self-assembling; requirements that we have previously defined as essential and necessary to create a profitable system. In addition, to take advantage of the ATP and NADH



produced by its photophosphorylation system, it requires the external addition of the enzymes involved in the Calvin cycle. Not only that, but the maximum efficiency peak results occur when the foam is constantly re-inflated (although this is a minor problem). In short, although it is an effective system, it is very expensive and unprofitable. The following work, by Liu *et al.* (2016), solves some of these problems. They created a hybrid system, which incorporates artificial photolytic machinery and a culture of bacteria that takes advantage of the hydrogen produced by this machinery to fixate CO<sub>2</sub>, in a relatively efficient and scalable way. “We developed a hybrid water splitting–biosynthetic system based on a biocompatible Earth-abundant inorganic catalyst system to split water into molecular hydrogen and oxygen (H<sub>2</sub> and O<sub>2</sub>) at low driving voltages. When grown in contact with these catalysts, *Ralstonia eutropha* consumed the produced H<sub>2</sub> to synthesize biomass and fuels or chemical products from low CO<sub>2</sub> concentration in the presence of O<sub>2</sub>. This scalable system has a CO<sub>2</sub> reduction energy efficiency of ≈ 50 % when producing bacterial biomass and liquid fusel alcohols, scrubbing 180 grams of CO<sub>2</sub> per kilowatt/hour of electricity. Coupling this hybrid device to existing photovoltaic systems would yield a CO<sub>2</sub> reduction energy efficiency of ≈ 10 %, exceeding that of natural photosynthetic systems.” This settles a solution to the problem of having to constantly add the enzymes of the Calvin cycle, since these are replenished by bacteria, but it presents the great disadvantage that it depends on the activity of living beings to perform their function, and these are delicate. They found several problems with this, as they stated that Reactive Oxygen Species (ROS) and toxic elements leaked from their cathode inhibited bacterial growth: “However, ROS produced at the cathode were detrimental to cell growth. Because hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), as well as short-lived superoxide (O<sub>2</sub><sup>•-</sup>) and hydroxyl radical (OH<sup>\*</sup>) species, are thermodynamically favoured against H<sub>2</sub> production at pH = 7, ROS production dominated at or below the potential to generate H<sub>2</sub>”. “In addition, leaching of Ni from the NiMoZn alloy into solution inhibited microbial growth”. These problems were, nevertheless, fixed later, by substituting the cheap Nickel, Molybdenum and Zinc (NiMoZn) cathode, made of Earth abundant materials, by a self-healing Co-P/Co-P<sub>i</sub> (Cobalt-Phosphorus) cathode, more expensive, but biocompatible.

In 2017, Ren *et al.* find the solution to most of these previous problems and, helped with the technology available so far, they design a cell-free photosynthetic platform, represented in **Figure 9**, which performs all the necessary functions to produce chemical energy from sunlight without intermediaries or external help; though they don't mention its efficiency. “We developed a cell-free artificial photosynthesis platform conducting both light and dark reactions for harvesting light energy and transforming the energy to organic compounds. To the best of our knowledge, such a device had not been reported so far. This system was able to harvest light energy and transform the energy to organic compounds, mimicking a plant leaf.”



**Figure 9** | Photography of the device created by Ren *et al.*: light and dark reaction units are integrated into a printed circuit board (PCB). Scale is in centimetres (cm) (Ren *et al.*, 2017).

Although idyllic, it also has a serious drawback, which all the methods described so far share in common: their very high production cost. It is no fortuity that Ren *et al.* wrote that this smart technology will be used in the future, referring to the time when it will be more economically accessible: “Lab-on-chip with capacitive biosensing using EIS technologies will be broadly used in cell-free biological system. ASIC combining with microfluidic structure can support intelligent analysis without the presence of cell during biochemistry reactions or processes. In the future, the ASIC technologies may improve the applications for intelligent operations for cell-free biochemical reactions environment”. The Non-Recurring Engineering (NRE) cost of an Application-Specific Integrated Circuit (ASIC) can run into the millions of dollars. Device manufacturers typically prefer ASICs for very large production volumes where NRE costs can be amortized across many devices. Until they cannot mass produce their system, it will be nowhere near profitability, and that would require a vast investment of money.

Finally, I highlight the device created by Chowdhury *et al.* (2018), as an exemplification of numerous works (not only theirs) that revolve around the idea that, since the reduction of carbon dioxide that occurs in the independent light phase of photosynthesis is the most complicated process to mimic artificially, perhaps it might be better to solely focus on the water-splitting to produce hydrogen and O<sub>2</sub>. This process is run very efficiently, thanks to great advances in the nanostructure of the photocatalysts employed. “We have demonstrated a photochemical (PC) diode artificial photosynthesis system that can enable efficient, unassisted overall pure water splitting without using any sacrificial reagent. By precisely controlling charge carrier flow at the nanoscale, the wafer-level photochemical diode arrays exhibited solar-to-hydrogen efficiency  $\approx 3.3$  % in neutral (pH  $\approx 7.0$ ) overall water splitting reaction. In part of the visible spectrum (400–485 nm), the energy conversion efficiency and apparent quantum yield reaches  $\approx 8.75$  % and  $\approx 20$  %, respectively, which are the highest values ever reported for one-step visible-light driven

photocatalytic overall pure water splitting.” In regards their durability, they affirm that “The photochemical diode nanostructures remain stable after the photocatalytic reactions, and negligible signs of degradation were observed after  $\approx 4$  h of overall neutral pH water splitting and hydrogen evolution reaction”.

Their system has several advantages over previous attempts of constructing viable water-splitting devices: Highest efficiency values were always obtained by PEC water-splitting, but that method is not suitable for neutral pH values. Chowdhury’s system reaches the highest ever value for the range of pH of seawater, which is the most probable source of water for future energy mass-production devices. Also, a common problem in PC water-splitting is the difficulty to separate the oxygen from the hydrogen once they are produced. Their creation allows a secure separation of those, thanks to its Indium, Gallium and Nitrogen (InGaN) nano-sheet structures. In their words, “In addition to the efficient charge carrier separation and extraction, the spatial separation of catalytic sites in such a nanoscale photochemical diode effectively reduces carrier recombination and back reaction”. Moreover, Chowdhury and their team affirm that their invention will also be used to augment the efficiency of the light-independent reactions of artificial photosynthesis, although they do not deepen more on that regard: “The capacity to achieve controllable charge carrier separation and extraction at the nanoscale will also be instrumental to break the efficiency bottleneck for artificial photosynthesis, including reduction of  $\text{CO}_2$  to hydrocarbon fuels”.

One can observe in many of the systems already designed, and that function with greater or lesser efficiency, the lack of scalability and longevity on their construction, and that to achieve a real panorama of energy production through photosynthesis, these must be enhanced. I do not intend to disregard the work of authors who have dedicated their time to creating semi- (or completely) functional systems, but of short duration or little size; their research is of prime, vital importance and his ingenuity and ability to create devices capable of producing chemical energy from sunlight from scratch, with current knowledge, reveals possible ways and mechanisms that will be used in future systems, fully profitable and operational.

## 5. Conclusions.

From the proposed objectives for this document, clear explanations have been given to tackle them, having successfully displayed what is the state of the art on the topics that are discussed.

It has been clarified what is the current status of  $\text{CO}_2$  emissions and its critical situation, which can be seen as an inflexion point towards worse environmental conditions for humankind.

Emphasis on artificial photosynthesis has been done, and it has been stated that this mechanism can theoretically be utilized as a manner to recover the integrity of the ideal environmental conditions for society to prosper.

As well, it has been clarified that this could be achieved through its implementation in large-scale as an energy producing system. In this regard, it has been discussed its actual viability, by scoping into what has been done to date in its research field, through three main perspectives: what is the current status of knowledge of the structures involved in the photosynthetic process, the advancements made so far to improve the scalability, longevity and efficiency of the components of artificial photosynthetic systems, and what fully functioning devices have been created so far. From this analysis I extract that, although several works have been done to clarify and elucidate the structures involved in the process, which could translate into more efficient devices, these advancements have not been successfully employed yet, as there are not viable/profitable devices to date. This is due to the low longevity, low scalability or low efficiency, or a combination of all these factors of the devices that I found to be more advanced and complete.

I conclude that, although a vast effort has been put into the elaboration of these devices, their low profitability makes the global deployment of an artificial photosynthesis energy production system certainly far from reach yet, although the bases are already set.

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Se han aportado explicaciones claras para abordar los objetivos propuestos en este trabajo, habiendo clarificado con éxito cuál es el estado del arte de los temas discutidos.

Se ha aclarado cuál es el estado actual de las emisiones antropogénicas de CO<sub>2</sub> y su situación crítica, que puede ser vista como un punto de inflexión hacia condiciones medioambientales perjudiciales para la humanidad.

Se ha hecho especial énfasis en la fotosíntesis artificial y ésta ha sido propuesta como un mecanismo que puede ser utilizado, teóricamente, como una vía para recuperar la integridad de las condiciones ambientales ideales que permitan a la sociedad prosperar.

Así mismo, se ha esclarecido que esto podría ser logrado a través de su implementación a gran escala como un sistema de producción de energía. En este aspecto, se ha discutido su viabilidad real, a través de una inspección de qué ha sido investigado hasta la fecha en el campo de la fotosíntesis artificial a través de tres puntos de vista: cuál es el estado actual de conocimiento de las estructuras envueltas en el proceso fotosintético, los avances hechos hasta la actualidad en cuanto a mejorar la longevidad y escalabilidad de los componentes de los sistemas fotosintéticos artificiales y qué aparatos completamente funcionales se han creado hasta ahora. De este análisis se extrae que, aunque hay numerosos trabajos dedicados a clarificar y dilucidar las estructuras envueltas en el proceso, y que estos avances se pueden traducir en mejoras en la eficiencia de los sistemas creados, dichos avances no han conseguido ser incorporados satisfactoriamente todavía, ya que, hasta la fecha, no existe un sistema rentable ni viable. Esto es debido a la baja escalabilidad, baja longevidad o baja eficiencia, o una combinación de todas, de los aparatos más avanzados y completos.

Para finalizar, se concluye que, aunque se ha puesto un enorme esfuerzo en la elaboración de estos aparatos artificiales, su baja rentabilidad hace que el despliegue de un sistema global de

producción de energía a través de la fotosíntesis artificial está ciertamente lejos del alcance aún, aunque las bases ya han sido puestas.

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Aportáronse explicacións claras para abordar os obxectivos propostos neste traballo, clarificando con éxito cal é o estado da arte dos temas discutidos.

Aclarouse cal é o estado actual das emisións antropoxénicas de CO<sub>2</sub> e a súa situación crítica, que pode ser vista como un punto de inflexión hacia condicións medioambientais perxudiciais para a humanidade.

Fíxose especial énfase na fotosíntese artificial e esta foi proposta como un mecanismo que pode ser empregado, teoricamente, como unha vía para recuperar a integridade das condicións ambientais ideais que permitan á sociedade prosperar.

Así mesmo, esclareceuse que isto podería ser logrado a través da súa implementación a gran escala como un sistema de produción de enerxía. Neste aspecto, discutiuse a súa viabilidade real, a través dunha inspección de que é o que foi investigado ata a data no campo da fotosíntese artificial a través de tres puntos de vista: cal é o estado actual do coñecemento das estruturas envoltas no proceso fotosintético, os avances feitos ata a actualidade en canto a mellorar a lonxevidade e escalabilidade dos compoñentes dos sistemas fotosintéticos artificiais e que aparatos completamente funcionais se crearon ata o de agora. Desta análise extráese que, aínda que hai numerosos traballos dedicados a clarificar e dilucidar as estruturas envoltas no proceso, e que estos avances pódense traducir en melloras na eficiencia dos sistemas creados, os devanditos avances non conseguiron ser incorporados satisfactoriamente todavía, xa que, ata agora, non existe un sistema rentable nin viable. Isto é debido á baixa escalabilidade, baixa lonxevidade ou baixa eficiencia, ou unha combinación de todas, dos aparatos máis avanzados e completos.

Para finalizar, conclúese que, aínda que se puxo un enorme esforzo na elaboración destes aparatos artificiais, a súa baixa rentabilidade fai que o despregue dun sistema global de produción de enerxía a través da fotosíntese artificial está certamente lonxe do alcance todavía, aínda que as bases xa foron postas.

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