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BIOLOGICAL SOLAR ENERGY: DEVELOPMENT OF ARTIFICIAL PHOTOSYNTHESIS FOR SUSTAINABLE ENERGY

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Abstract- *This paper reports using biological solar energy as a substitute to fossil fuel in energy generation. The need for biological solar energy and the processes involved in generating energy through this means has also been investigated and analyzed. The paper also examined artificial Photosynthesis as a means of biological solar energy to create clean and sustainable energy. Artificial Photosynthesis manufactures nature-inspired machinery that directly change sunlight into fuel and electricity. It is achieved using biological photosynthetic material to attract solar energy and generate and store it efficiently. Artificial Photosynthesis is achieved by either designing a prototype sun that can supply the required photons to be captured by plants for the photosynthetic process or creating artificial plants that can efficiently capture sunlight for the photosynthetic process. This energy source has the prospect to supply the world's enormous energy needs and combat climate change if adequately harnessed.*

Keywords- Biological Solar Energy; Artificial Photosynthesis, Biomass, Light–Dependent Reaction; Light-Independent Reaction; Sustainable Energy.

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Introduction

Most of the energy available globally today to run our devices, heat our houses, and create various chemicals and raw materials that maintain our day-to-day activities is directly or indirectly generated through the process of Photosynthesis [1], [2].Fossil fuel is one of the significant sources of energy produced through the process of Photosynthesis in ample quantities. Currently, the amount of fossil fuel available globally is abundant enough to give us the energy needed; however, it is more apparent that this type of energy is not environmentally friendly and unsustainable[3], [4]. Specifically, the dwindling quantities of fossil fuels available for consumption, the rising level of carbon dioxide in the atmosphere, and the effects of global warming are the significant challenges associated with this type of energy[5]. Based on the previous, there is enormous research interest in renewable energies generated via natural resources as a suitable alternative to fossil fuels[6].Solar energy is the primary natural energy source with enormous potential adjudged to be abundant, cheap, clean, and sustainable [7], [8]. However, it cannot be used directly for practical purposes unless harnessed into usable energy formslike green plants. Recent research interest has risen towards converting energy from the sun to chemical bonds and storing it in stable organic molecules just as plants do in ordinary Photosynthesis[9], [10].

Photosynthesis is a means by which organisms, primarily plants, utilize light energy from the sun and convert the energy into the organic molecules of biomass. Typically, photosynthetic organisms attract energy from the sun and transformed it into ATP (Adenosine triphosphate) and NADPH (Nicotinamide adenine dinucleotide phosphate),which are necessary for carbon dioxide fixation [6], [11]. The success and efficiency of the photosynthesis process as an energy generation and storage system are high because of the abundance of the required raw materials (sunlight, water, and carbon dioxide) in abundant quantity[9], [11]–[13]. The Photosynthetic process involves two significant separate reactions: the light-dependent reaction, known as the light reaction, and the light-independent reaction,known as the dark reaction. The light-dependent reaction involves four significant events: light absorption via antenna chlorophyll, charge separation, water splitting, and electron/proton transfer. The water splitting by the sunlight produced hydrogen and oxygen. While oxygen is circulated into the atmosphere for respiration in animals and for burning of fuels, the hydrogen is not released into the atmosphere but rather combines with carbon dioxide to produce sugars and some types of organic molecules [6], [9], [14], [15]. The hydrogen is used up when it combines with atmospheric oxygen during the burning of biofuels, biomass, and fossil fuels to produce energy. Besides, the combination of oxygen and hydrogen takes place during respiration.

So far, it's shown that Photosynthesis produce a model of solar energy storage in fuels (solar fuel),and the knowledge when well put to use, can give well-built technologies for storage, supply, and use of solar fuel that can compete with fossil fuel.Artificial Photosynthesis, which apply the basic science underlying photosynthetic energy transformation to design synthetic systems for changing light into stored chemical energy, seems to answer man's quest for an abundant, inexpensive, pure, and sustainable energy source.

This review paper will analyze the natural photosynthesis process and utilization of biological solar energy. We will also explore the development of artificial Photosynthesis and, finally, the deployment of artificial Photosynthesis to combat climate change.

1.0 Related Works

Kathpalia and Anita [16] in their chapter contribution to a book titled 'artificial photosynthesis an alternative source of renewable energy: potentials and Limitations' provides an extensive view of the artificial photosynthesis system, its limitations, the challenges, and the future scope of artificial photosynthesis as an alternative source of energy. Andrew et al. [17] investigated photoelectrochemical cells for artificial photosynthesis as an alternative to water oxidation. In the review, an assessment of viable alternatives to water oxidation that can be incorporated into photoelectrochemical cells was carried out. Jenny et al. [18] worked on biophotovoltaics as a green power generation from sunlight and water and provides a highlight on the setup configurations and experimental designs of biophotovoltaics research in the past. They discussed the key parameters that govern the major characteristics of a BPV system thereby providing a guide for tailoring the appropriate measuring platform. Dogutan and Nocera [19] researched artificial photosynthesis with efficiencies greatly exceeding that of natural photosynthesis. Several ways to improve the efficiencies of artificial photosynthesis were investigated. Sudhakar et al. [20]reviewed the topic 'artificial leaves: towards bio-inspired solar energy converters' in which they review the theory of artificial leaves and provide a detailed analysis of the artificial leaves arrangement. The challenges involved in artificial leaf technology were also investigated. El-Khouly et al. [6] reviewed the topic 'Solar energy conversion: From Natural to artificial photosynthesis. In the review, the authors highlighted the current trends of natural, semi-artificial, and artificial photosynthesis in terms of concepts, design, and examples. The review focused on the molecular level of natural photosynthesis particularly photosystem I and photosystem II, light-dependent reactions in oxygen-evolving organisms, and so on. Purchase and Groot [5] studied bio-solar cells and shows that global artificial photosynthesis needs responsive matrices with quantum coherent kinetic control for high yield. Mckone et al. [21] outlined key constraints that inform research efforts in the area of integrated systems for solar-driven water electrolysis. Thapper et al. [22] researched the topic of 'artificial photosynthesis for solar fuels and reported on the social goals in energy research after describing solar fuels and artificial photosynthesis. Zhou et al. [23]researched artificial inorganic leaves for efficient photochemical hydrogen production inspired by natural photosynthesis. Their approach to artificial photosynthesis was to construct an artificial leaf by copying the complex architecture of leaves and replacing the natural photosynthetic pigments with mam-made catalysts to realize efficient light harvesting and photochemical hydrogen production. Gust et al. [12] investigated solar fuels via artificial photosynthesis and highlight the recent experiments in artificial photosynthetic fuel production.

3.0 The Process of Natural Photosynthesis

Energy is needed by all living organisms for productivity, growth, and upkeep. For most species, this energy is obtained from the sun either directly or indirectly, and Photosynthesis is the initial process of using solar energy. Photosynthesis is the manufacture of organic molecules, mainly sugar from Carbon dioxide (CO_2) and water (H_2O), in the presence of sunlight energy or the process by which sunlight energy is changed into chemical energy of carbohydrate molecules.

$$6CO_2 + 6H_2O \xrightarrow[Chlorophyll]{Sunlight} \underset{Carbohydrate}{C_6H_{12}O_6} + \underset{Oxygen}{6O_2} \quad \Delta G = 522\,kJmol^{-1}$$

It simply shows that the process of Photosynthesis is a biochemical process of storing energy from the sun in plants, microorganisms, and even bacteria, and it provides the energy needed for life activities on Earth (McKone et al., 2014; Sudhakar & Mamat, 2019) and the oxygen to support respiration in animals (Zhou et al., 2010). The products of the process of Photosynthesis are carbohydrates (energy) and oxygen. As seen in the chemical reaction equation, the process of Photosynthesis needs carbon dioxide, water, sunlight, and the pigment chlorophyll to occur.

$$Photosynthesis + solar\ Energy \rightarrow Energy\ \ for\ Life\ Activities$$

Photosynthesis involves three critical steps:CO_2 diffusion, the photochemical step, and the biochemical action. Diffusion is the first step, and it consists of the vapor phase diffusion of CO_2 from the air, which contains almost 0.04 % CO_2, through the stomata to the intercellular spaces, then the liquid phase diffusion to the chloroplast, which is the site where Photosynthesis takes place [24].

The photochemical step involves the light-dependent reaction,which takes place in the chloroplast's thylakoid membrane[20], [25]. The thylakoid membrane contains the green chlorophyll pigment and other pigments.

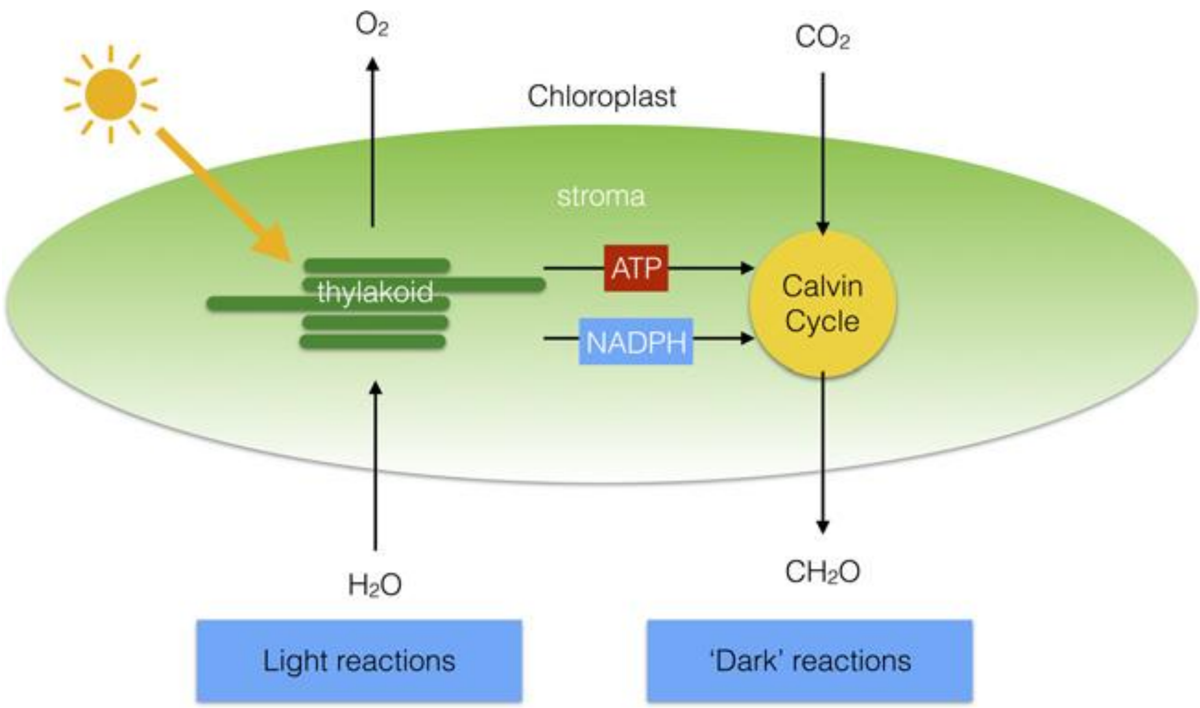

Fig.1: Light reaction in the thylakoid and Dark reaction in the chloroplast stroma [26].

These pigments and related proteins are grouped to form units known as Photosystems. Two types of Photosystems, known as photosystem I (PSI) and photosystem II (PSII), are identified. Each photosystem contains the most crucial chlorophyll *a* and accessory pigments chlorophyll *b* and carotenoids. The Essential chlorophyll *a* pigment is denoted by P700 and P680 for PSI and PSII, respectively, indicative of the most efficiently absorbed light wavelength by these pigments, PSI and PSII[27]. The chlorophyll pigments take in primarily the red and blue light wavelengths reflecting and transmitting green wavelengths, thereby making the leaves of plants green. The wavelength of light energy absorbed by the accessory pigments is a bit different from that absorbed by chlorophyll *a*, and this energy is directed to chlorophyll *a* for the process of Photosynthesis. PSI and PSII are necessary for the operation of Photosynthesis, especially in the case of higher plants [24], [28]. The light-driven Water-

Splitting reaction occurs in an enzyme known as PSII available in plants, cyanobacteria, and algae[1], [26]. During this reaction, four major events occur, Viz., light harvesting involving the absorption of sunlight, charge separation, water splitting, and fuel production [29]. The light-dependent reaction produces NADPH (Nicotinamide Adenine Dinucleotide Phosphate) and ATP (Adenosine Triphosphate). The production of NADPH is done in the PSII. Typically, PSII absorbed solar energy, producing an electron excitation from P680 to an excited state. The electron in the excited state is quickly moved to a primary electron–acceptor molecule linked to P680 to prevent it from falling back to the ground state in P680 and emitting energy. At this point and in the PSII, the electron is immediately moved from one acceptor to another resulting in an electron transfer chain. The energy of the excited electron in the transfer chain is used to transfer H^+ (proton) in the stroma to the lumen of the thylakoids. A mobile electron acceptor transports the electron to PSI,which is moved to P700. By giving out electrons, the pigment P680 in PSII has fewer electrons and becomes an oxidizing agent. The pigment P680 in PSII, an oxidizing agent,can split water molecules and produce protons which are amassed in the lumen of the thylakoids, as shown in the reaction below.

$$2H_2O \rightarrow 4H^+ + 4e^- + O_2$$

The electron provided by P680 in PSII to P700 in PSI gains energy from the light energy absorbed by P700 in PSI, and it is moved to an excited state where it is also quickly transferred to a primary electron acceptor linked to PSI, where it moves in a transfer chain and eventually transferred to $NADP^+$. This produces a powerful reducing agent NADPH. The reaction occurs on the stroma of the thylakoid membrane.

$$NADP^+ + 2e^- + H^+ \rightarrow NADPH$$

Adenosine triphosphate (ATP) is produced by a process known as photophosphorylation. The process makes use of solar energy to generate high-energy phosphate bonds. In this reaction, protons (H^+) concentration gradient is created across the thylakoid membrane due to a large concentration of proton in the lumen of the thylakoids and a depletion of the same in the stroma. This cause the flow of protons from the lumen to the stroma via ATP synthase, a membrane protein resulting in electrical energy flow used by ATP synthase to produce ATP from Adenosine diphosphate (ADP) and $P_{i,}$ an inorganic phosphate.

$$ADP + P_i + Energy \rightarrow ATP$$

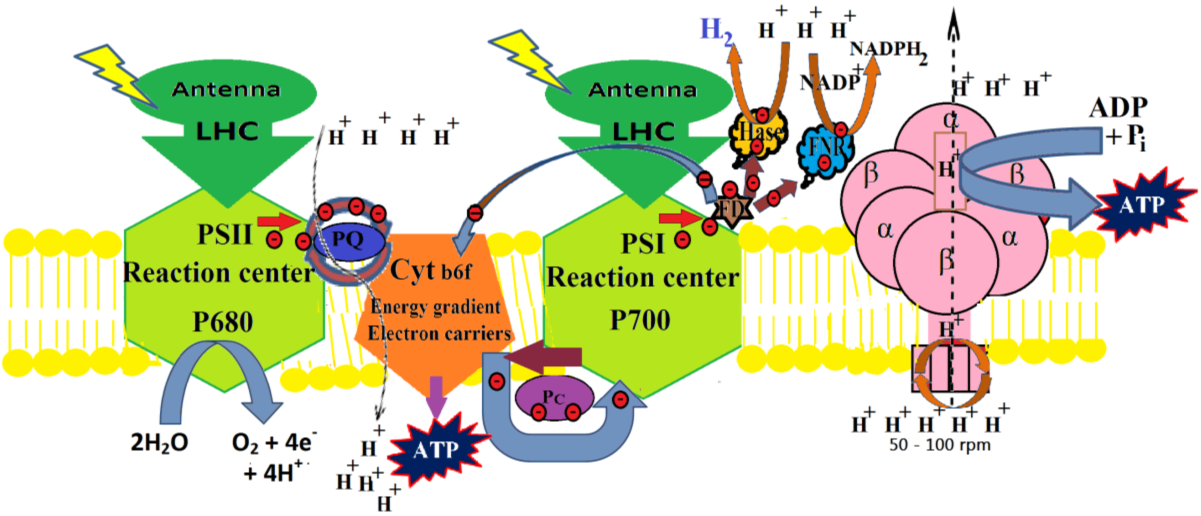

Fig. 2: Light-dependent reaction electron flow chain [6].

The last step is the biochemical step which involves mainly the dark reaction, also known as the light-independent reaction. Here the NADPH and ATP produced in the photochemical step are used along with the carbon dioxide to form glucose molecules which are organic compounds.

$$3CO_2 + 9ATP + 6NADPH + 6H^+ \rightarrow C_3H_6O_3 - Phosphate + 9ADP + 8pi + 6NADP + 3H_2O$$

Light–independent reaction (Kelvin-Benson Cycle) takes place in the stroma of the chloroplast in the absence of light [20], [30].

4.0 Utilization of Biological Solar Energy and Efficiency of Photosynthesis

Biological solar energy, called clean energy, is generated through biological photosynthetic material to attract energy of the sunand directly generate and store energy efficiently. One primary end product of Photosynthesis is biomass,which is effectively applied to produce heat, electricity, biogas, syngas, and biofuels (ethanol) [31]. The efficiency of conversion of solar energy (which the sun provides at an average rate of 100 000 TW) by Photosynthesis to biomass is very low, about 0.1 to 1.0 % efficiency based on origin. However, the use of biomass worldwide annually represents an energy consumption rate equivalent to 1.4 TW. In the United States, biomass provides more than 3% of the country's energy needs, corresponding to a mean annual output rate of almost 0.1 TW [1]. Approximately 79 percent of the country's energy is produced using fossil fuels, 8.4 percent uses nuclear energy, and 12.5% uses renewable energy sources. Regarding the amount of energy supplied to the United States in 2019, renewable energy,notably biomass, overtook coal, and this trend persisted in 2021 [32].

Today's world annual energy requirement stands at 20 TW; therefore,using only biomass to meet this energy need is a big challenge. Biomass can be used to meet this energy need only if more than 30% of the land on Earth is used for crop production. However, this will create food shortages and crises. Therefore, using biomass crops with solar energy conversion efficiencies close to the theoretical maximum of about 4.5 % seems to provide an answer. Scientists could use the principles of natural Photosynthesis to create an efficient, entirely artificial, molecular-level energy conversion system.

Thorndike (1996) calculated the efficiency of Photosynthesis using the relationship provided below and obtained a value of 4.5 % when $hv_o = 680\,nm$, $\eta_O = 0.73$, $\eta_L = 0.5$, $\eta_S = 0.32$, $\eta_R = 0.80$, and $\eta_T = 0.50$.

$$F = \eta_T \eta_R \eta_S \eta_L \eta_O hv_o$$

From the equation η_O is the thermodynamic efficiency, which accounts for the entropy loss due to conversion from solar light energy to chemical free energy, η_T is a correction factor for saturation effect, η_R represents a correction factor for the reflectivity of a leaf, η_S stands for the spectral distribution of light, η_L stands for a factor which takes into account irreversibility energy losses in biochemical processes, photochemical reactions, and many other cellular and physiological processes and hv_o represents photon energy at the maximum frequency of conversion which is the red photon[9].

Research has shown that the yield of biomass produced by crops is at efficiencies less than 1% even at optimum fertilizer application and water supply. The major factors such as weather conditions, amount of light energy absorbed, soil nutrients, and water supply contribute to a reduction in the efficiency below the maximum of 4.5%. Despite low efficiency, biomass is the best substitute to fossil fuels as its production and usage are carbon-free and sustainable.

5.0 Artificial Photosynthesis

Artificial Photosynthesis is the creation of biomimetic machinery that directly converts sunlight into fuel and or electricity [22]. Artificial Photosynthesis can be mimicked in two ways. The first approach is to design and manufacture an artificial sun that can supply efficient sunlight energy to natural plants for Photosynthesis[33]. The second approach is to design and produce an artificial leaf (artificial plant) that mimics the natural plant[23], [34]. In this second approach, the natural photosynthesis process can be spoofed. An artificial photosynthesis system can be developed consisting of light harvesting, charge separation, water splitting, and fuel production units[14]. Artificial Photosynthesis is possible with artificial antennas, artificial reaction centers, photo-induced charge separation, water oxidation catalyst, Carbon dioxide reduction catalyst, and a regulation and photoprotection system. The light-harvesting unit consists of antenna molecules that capture the photons of sunlight and direct the energy to the reaction center (RC). At the reaction center, the charges are divided into holes and electrons using the solar energy that has been captured. The strong electromotive force generated by the reaction center element drives the oxidation and reduction reactions. The holes are directly injected into the catalytic sites to split water into hydrogen ions (protons) and oxygen. The oxidation catalyst is used to produce this reaction. The increased energy that the new photons provide to the separated electrons during the charge separation step causes them to react with the hydrogen ions and likely CO_2 to form either carbon-based energy or H_2. A reduction catalyst is used to carry out this process. This shows that the fundamental elements that drive the process describe above include antenna, reaction centre, oxidation catalyst and reduction catalyst. The construction of artificial photosynthesis system may therefore need four important components including light absorbers, catalysts, membrane and linkers [12], [20].

6.0 Conclusion and Future Scope

Solar energy is one primaryenergy source used directly or indirectly to provide man's energy need globally. Photosynthesis provides a means of converting solar energy into different forms of energy. Fossil energy is abundant and sufficient to give the global energy need; however, it has environmental challenges and is unsustainable. The major challenges associated with this type of energy are typically the dwindling quantities of fossil fuels available for consumption, the rising level of carbon dioxide in the atmosphere, and the effects of global warming. This calls for concern and intense research on renewable energies generated through natural resources as a suitable substitute to fossil fuels.It is possible to transform solar energy into chemical bonds and store it in stable organic molecules, just as plants do in natural Photosynthesis. This is done via artificial Photosynthesis, which manufactures nature-inspired machinery that directly converts sunlight into fuel and electricity. Artificial Photosynthesis may be achieved in two ways: designing a prototype sun that can supply the required energy (photons) to be captured by plants for the process of Photosynthesis or designing artificial leaves that can efficiently capture sunlight for the photosynthetic process. Though attempts have been made in this regard, developing and testing a practical prototype sun or artificial leaf has been the subject of intense research yet to yield accurate results for future industrial applications.

Conflict of Interest

Authors declare that they do not have any conflict of interest.

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Authors Contribution

Engr. Odoh Micheal conceived the study and wrote the first draft. Dr. Celestine Mbakaan reviewed and edited the manuscript. All authors approved the final version of the manuscript.

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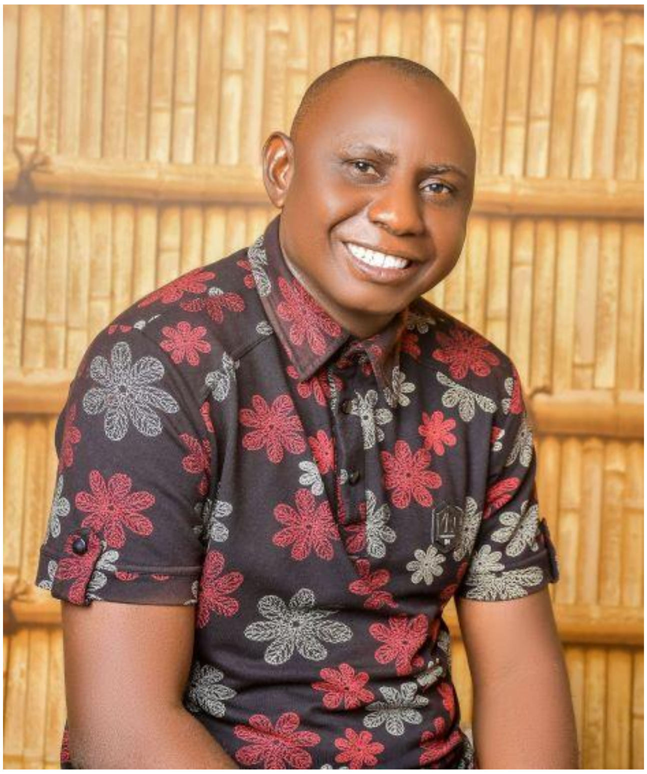

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