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The Enhancement Performance of Bio Solar Cells by using Gold Nanoparticles

Saeideh Golmohammadi[1], Edris Faizabadi, Gholamhossein Riazi[2] , Rasul Ajeian[1,*]

[1]School of Physics, Iran University of Science and Technology, Tehran, Iran
[2]Institute of Biochemistry and Biophysics, Tehran University, Iran

[*]**Corresponding Author:** Rasul Ajeian, School of Physics, Iran University of Science and Technology, Tel.: +98 (912) 218-7859, E-mail: Rasul_aj@iust.ac.ir

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Abstract

Photovoltaic solar cells have been a promising solution to the world's environmental air pollution in recent decades. However, despite their usage, Earth pollution has still been a concern. As a result, bio-solar cells have been researched among bio-physical researchers since 2012 to provide an environmentally compatible alternative. To increase the efficiency of bio-solar cells, gold nanoparticles have been employed along with chlorophyll extracted from spinach leaves. The nanoparticle model has proven to be more efficient, increasing current and voltage compared to previous models. In our experiments, we developed gold nanoparticles (AuNPs) in PS1 and PS2 active layers and the performance of the photovoltaic synthesized outputs was appropriate. Our bio solar cell, which consisted of Au/(Photosystem + Triton X-100 + GNP)/FTO, exhibited superior photovoltaic efficiency at 0.32%. Parameters such as short-circuit current density (JSC), cut-off voltage, and fill factor converged to values of 0.099 mA/cm^2, 0.107 V, and 0.25, respectively. Based on our observations, this structure is a promising candidate for sustainable solar energy production.

Keywords: Bio Solar Cell; Nanoparticle; Organic Electronics; Bio Semiconductors

Introduction

Solar cell technology is increasingly popular for generating electricity. The photovoltaic effect is the fundamental principle behind solar cells, converting light into electricity. One of the most significant advantages is that solar energy is a renewable resource. Despite the reported advantages, some challenges are associated with using solar cells to generate electricity. [1-7].

Solar cells are divided into mono-crystalline silicon-based (C-Si), thin-film solar cells, and organic solar cells. Despite having good performance, the three previous solar cell productions posed pollution problems due to waste [8-10]. In contrast, bio solar cells – we mean the fourth generation of solar cells - are the most environmentally friendly.

A biosolar cell is a solar cell, which uses light-harvesting proteins found in photosynthetic organisms to convert sunlight into electrical energy [11, 12]. In biosolar cells, protein complexes of green plants act as natural photodiodes, replacing p-n junctions. In our experiments, we use the photosystem 1 and 2 from young spinach as an active layer. [13, 17]

Although proteins possess an internal quantum efficiency of around 100% with an external quantum efficiency of approximately 50% and a short relaxation time of about 10^{-12} to 10^{-14} seconds, the actual efficiency of these solar cells remains relatively low.

They involve evaluating both external quantum efficiency (EQE), which measures the percentage of incident light converted into electricity, and internal quantum efficiency (IQE), which gauges the effectiveness of light absorption and charge generation within the device or organism. Understanding these parameters is crucial for optimizing bio-solar cells' sustainable energy potential and plant protein photosynthetic capabilities. [19-22].

One notable advantage of bio-solar cells is their remarkable internal quantum efficiency (IQE), which may reach an impressive 100%. IQE represents the efficiency which absorbed photons are converted into charge carriers (usually electrons) within the solar cell. In the case of bio-solar cells, this efficiency is exceptionally high, primarily due to the natural photosynthetic processes utilized by biological organisms such as algae or bacteria. Unlike some traditional solar cell technologies which may suffer from losses due to energy dissipation as heat. Bio-solar cells maximize the utilization of absorbed sunlight, ensuring that nearly every photon contributes to electricity generation. This extraordinary level of internal quantum efficiency underscores the potential of bio-solar cells as a highly efficient and sustainable renewable energy source, offering a favorable pathway towards a greener and more efficient future in energy production. [23-25]

These types of solar cells represent a favorable area of research in renewable energy.

Due to the chlorophyll-based solar cells, significant research projects are dedicated to enhancing various aspects such as protein purification, efficiency, and stability.

Back in 2012, Vanderbilt University in the United States made a groundbreaking discovery by incorporating photosystem 1 as a pigment in a P-type silicon solar cell. This significant achievement was reported on the university's website, detailing the collaboration between David Cliffel and Co. As per Cliffel, this integration resulted in current levels that were nearly 1,000 times higher than those achieved by depositing the protein on various metals, alongside a slight boost in voltage [26].

Solar cell research in the thin film state was initially conducted independently by the University of Science and Technology in Iran and the University of Groningen in the Netherlands. They published an article in Advanced Materials in 2014 on this topic [27], which sparked further research on solar cells that use photosystems as an active layer (monolayer). The Iran University of Science and Technology department later published research articles on this topic in 2017, including work by Kazemzadeh et al. [28] Kazemzadeh’s research achieved an efficiency of 0.069% using flat layers with the order of FTO/PEDOT: PSS/P-

S1/LiF/Al. On the other hand, Zeynali et al. [29] obtained an efficiency of 0.5% by producing uneven surfaces using C60 and tyrosine, by the order of ITO/tyrosine/PS1/C60/Au. using PY-PANI as the hole transfer layer, PSI as an active layer, and reduced graphene oxide as an electron transfer layer, Voc=0.3 V, Jsc=5.6mAcm_2, and an efficiency of 0.64% were achieved by Torabi et al. [30]

In a review published by Ewha Womans University, Seoul, several projects were mentioned as examples of solid-state solar cells based on PS1. [31]

Our laboratory focuses on exploring different materials, layering techniques, underlying structures, and the effects of electrical fields. [32-33] Additionally, we've investigated extraction methods, extraction buffers, absorption analysis of Photosystem I in different plants, and other related factors to contribute to advancing this promising technology. [34] Through these efforts, we have achieved significant improvements in efficiency and continue to work towards further enhancements. In our experiments, we have seen efficiency rates ranging from 0.022% to 0.5%, and we are currently refining our methods to achieve an efficiency of 0.75% and beyond.

Low efficiency and low current density are the main challenges in this kind of solar cell. However, upon reviewing previous researches, it was observed that there had not been a comprehensive study on the effect of Au nanoparticles in biosolar cells, such as Au/(Photosystem + SDS + GNP)/FTO, Au/(Photosystem + Triton X-100 + GNP)/FTO, and Au/(Photosystem + GNP)/FTO. To address this gap, we conducted a study where we added a layer of Triton X-100 over the active layer that contains nanoparticles, as shown in Figure 1. Transfer layers play an important role in increasing the efficiency of solar cells, which has been considered in previous works such as tyrosine which is one of the amino acids that play an important role in photosynthesis. When electrons are produced in the Mn_4CaO_5 cluster of PSII as a result of water oxidation, these electrons can reach pigment P_680 via tyrosine. [35, 37] Furthermore, tyrosine can create a porous surface that increases the amount of sunlight absorption.

Metal nanoparticles such as gold and silver have been used in different solar cells [38-41] to increase their efficiency, Unlike the previous works, we used them in our solar cells as an absorber layer, in addition to changing the transfer layers (electron and hole), the absorbing layer was changed. We also incorporate Triton X for transfer, which, like carbon nanotubes used in earlier research, helps direct electron pathways. By combining Photosystem and gold nanoparticles (AuNPs) solutions, we can enhance light absorption and increase current density, leading to greater efficiency in this particular type of solar cell.

Herein, to vacillate the motion of electrons and holes, tyrosine is used as a transfer layer and to increase light absorbance, a solution of Photosystems with gold nanoparticles as an absorber layer is used.

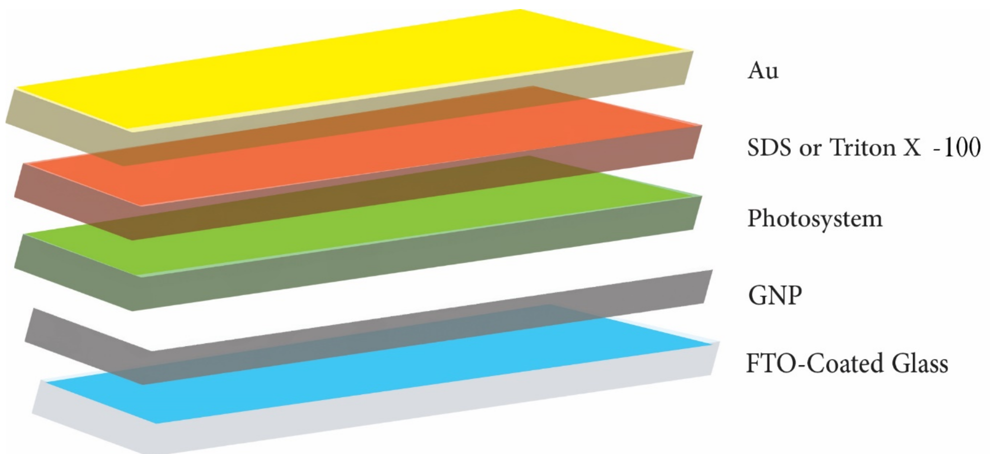

Figure 1: Bio-organic solar cell stack (FTO/GNP/Photosystem/Triton X-100/Au)

Experimental Method [42]

Photosystem Extraction Process

Fresh spinach leaves from the market were first washed and dried to extract photosystems from spinach leaves. Then, Spinach leaves were washed and dried to extract photosystems. A 40 ml sample was prepared, blended with a buffer mixture, then filtered. The colloidal solution was centrifuged twice at different speeds to release thylakoids. The chloroplast wall was damaged through homogenization. Chlorophyll was measured using acetone and a final centrifugation of 3-4 minutes based on Kazemzadeh's protocols [28].

Breaking the Thylakoid Membrane

We used Triton X-100 and Sodium Dodecyl Sulfate (SDS detergents) separately to treat 1mg chlorophyll solution. After adding the detergents, we homogenized the mixture for 15 minutes to ensure the distribution of detergents and to break down the thylakoid lipid double membrane. Finally, we centrifuged the homogenized solution for 15 minutes at 15000 rps.

Gold Nanoparticles Synthesis

Gold nanoparticles (AuNPs) were synthesized through a photochemical process involving ultraviolet (UV) radiation to reduce gold ions from a gold-containing precursor like chloroauric acid. The process starts with preparing a solution containing the gold precursor, stabilizing agents, and surfactants. The solution was exposed to UV radiation, which initiates photochemical reactions resulting in the reduction of gold ions and the formation of nanoparticles. Researchers adjust various parameters to fine-tune the characteristics of the nanoparticles. This method provides a precise and adjustable way of producing nanoparticles for different applications in science and technology. Top of Form. Gold nanoparticles were synthesized using the photochemical method and micelle formation from TritonX-100. To achieve this, a prepared solution of chloroauric acid and TritonX-100 sample was exposed to UV radiation at ambient temperature. The distance from the radiation source was varied during the procedure to obtain gold nanoparticle size. This distance was altered from 2 cm to 20 cm. Figure 2 illustrates the nanoparticles produced at different lengths [43-52]. (Change the particle size by light source distance indicated by the photochemical method.)

The UV radiation distance from the solution directly influences the characteristics of the nanoparticles. This parameter was carefully optimized to ensure uniform radiation distribution and prevent the formation of nanoparticles with varied sizes. The selected distance allows for optimal control over the rate of UV energy absorption and metal ion reduction, leading to nanoparticles with desirable properties. Increasing the distance could result in larger particles and morphological changes, while a smaller distance could produce non-uniform particles. Additionally, color changes in the solution served as an indicator of successful nanoparticle formation. A red hue indicated well-synthesized small gold nanoparticles, while a shift to purple or blue suggested aggregation, which would reduce the performance of the nanoparticles.

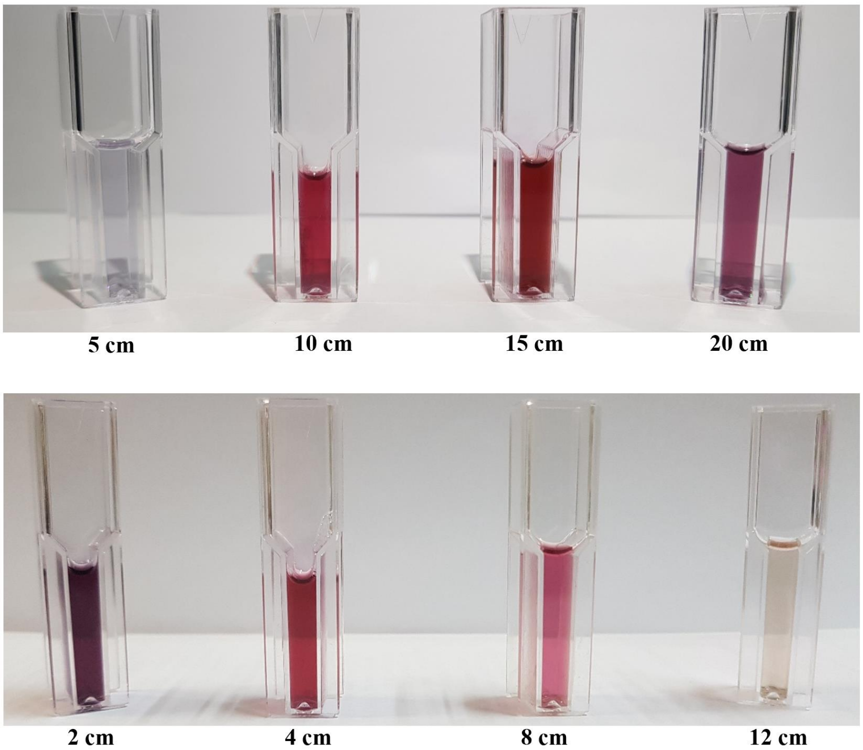

Figure 2: Synthesis of Au nanoparticles by photochemical method at different distances from the radiation source

Bio Solar Cells Production

Bio solar cells were prepared by extracting the photosystem protein from spinach leaves and synthesizing Au nanoparticles. The module structure was made by the cleaned electrode (FTO). The transparent electrode used for solar cell synthesis is called "FTO." The FTO-coated glass is cut to the desired dimensions using a diamond pen. After chemical cleaning, the sub-layers are washed with acetone, isopropanol, and deionized water in an ultrasonic machine. Surface ozone activated in UV device.

To start the cell synthesis process, a very thin layer of Triton X by doping, was applied and carefully drowed a protein layer onto the entire substrate using a syringe (taking care not to create any foam). After that, the nanoparticles were introduced using the drop method, requiring only 1-2 drops due to the high concentration of the solution. Finally, the substrate is left to dry under a clean box for one day to complete the protein layer. As a final step, a Gold layer was used by spin-coating.

Results and Discussion

Experimental Method Outputs

A photovoltaic system was synthesized in the presence of standard conditions of Au nanoparticles in three systems.

System A: Au/(Photosystem + SDS + GNP)/FTO

System B: Au/(Photosystem + Triton X-100 + GNP)/FTO

System C: Au/(Photosystem + GNP)/FTO

In order to photovoltaic performance of these systems, we examined physical properties such as short-circuit current density (JSC), cut-off voltage, fill factor, and efficiency. Figure 3 in this section shows the I-V curve outputs for all three systems in a graph of several samples. Our results showed that the Au/(Photosystem + Triton X-100 + GNP)/FTO sample exhibits superior photovoltaic qualities.

JSC represents the amount of electrical current that flows through a material during a short circuit. It is typically measured in amperes per square millimeter and is utilized to establish the maximum current-carrying capability of a conductor. As reported in Table 2, our findings indicate that the Au/(Photosystem + SDS + GNP)/FTO sample has a higher JSC of 1.90 mA/cm2. This suggests that more photons are absorbed by this atomic sample in real-world applications.

After conducting an analysis, we have discovered that the low photovoltaic efficiency in this structure is caused by the SDS sample which disrupts the atomic unity in the system. As a result, a significant number of absorbed photons in Au/(Photosystem + SDS + GNP)/FTO are lost. However, it seems that using SDS as a separate layer has aided in the adhesion of the layers.

In our study, the efficiency of bio-solar cells, optimized with gold nanoparticles, reached approximately 0.32%. Previous studies did not incorporate nanoparticles into bio-solar cells. To explore the impact of nanoparticles, a colleague in our group worked with silver nanoparticles, while I focused on gold nanoparticles. Experimentally, this should lead to an increase in efficiency, and past experience has shown that the use of certain nanoparticles can indeed enhance performance. However, more extensive research is needed to understand the underlying mechanisms fully.

Other researchers have approached the topic from different angles. For instance, the Groningen group used a monolayer structure, while we employed a multilayer approach, which we believe has contributed to our enhanced efficiency. Additionally, most groups have used cyanobacteria in their studies, whereas we utilized plant proteins, which sets our work apart. Many groups, including Groningen, relied on monolayers, while our group focused on multilayer structures and various parameters, including the integration of nanoparticles.

Our findings are unique in several ways. First, we were the first to introduce nanoparticles into this type of bio-solar cell study, which significantly boosted efficiency. Unlike most research groups that used cyanobacteria or monolayers (like the Groningen group), we used plant proteins and a multilayer structure. Additionally, incorporating gold nanoparticles, in contrast to silver or other materials, provided improved optical and electrical properties, contributing to the higher efficiency observed. These innovations suggest that further research into different nanoparticle types and their integration with biological systems could lead to even greater advancements in solar cell technology.

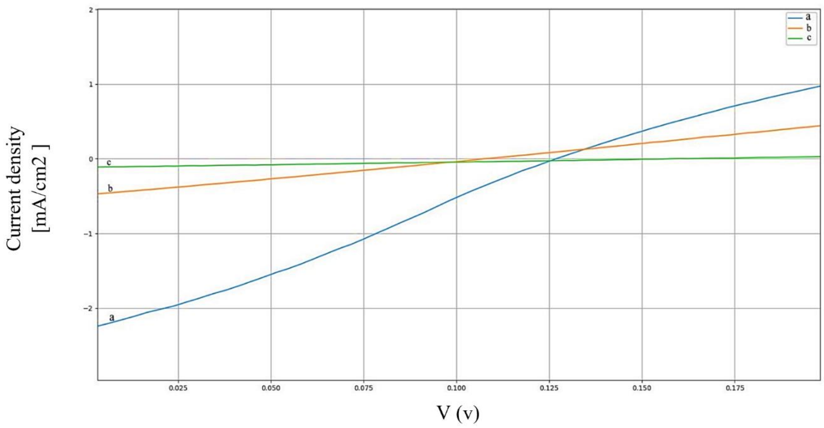

Figure 3: The I-V curve of synthesized solar cells as (a) Au/(Photosystem + SDS + GNP)/FTO, (b) Au/(Photosystem + Triton X-100 + GNP)/FTO, and (c) Au/(Photosystem + GNP)/FTO systems.

The cut-off voltage is a vital parameter for electronic devices, indicating the minimum voltage required to maintain optimal performance. Devices may malfunction or shut down completely if the voltage falls below this level. Decreasing this parameter can enhance the photovoltaic efficiency of the photosynthetic system. The Au/(Photosystem + Triton X-100 + GNP)/FTO system has the lowest cut-off voltage (0.107 V) compared to other systems. Therefore, we can expect this sample to have maximum photovoltaic efficiency (0.32%). Additionally, the structural integrity of photosynthetic systems is crucial for their use as active layers in solar cell arrangements. The FF parameter can describe this unity. It is the ratio of the maximum power output of the cell to the product of its open-circuit voltage and short-circuit current. FF represents the extent to which the cell can convert sunlight into electricity. In the Au/(Photosystem + GNP)/FTO sample, FF reached its maximum value (0.26), as listed in Table 1. This parameter optimizes the predicted interatomic distance, and charge carrier transitions occur efficiently in this sample.

Table 1: The photovoltaic parameters for various designed photosynthetic solar cells in current research

Sample ID	**Efficiency(%)**	**FF**	**Cutoff Voltage(V)**	**J_{sc}(mA/cm^2)**
A	0.07	0.24	0.13	1.90
B	0.32	0.25	0.107	0.099
C	0.15	0.26	0.157	0.051

Conclusion

In this study, we synthesized three types of bio solar cells, namely Au/(Photosystem + SDS + GNP)/FTO, Au/(Photosystem + Triton X-100 + GNP)/FTO, and Au/(Photosystem + GNP)/FTO. These solar cells were synthesized in the lab and their photovoltaic performance using the short-circuit current density (JSC), cut-off voltage, fill factor, and efficiency quantities.

To improve light absorbance, we added AuNPs to the absorber Photosystem layer. The localized surface plasmon resonance of AuNPs increases the light absorbance and thus increases the generation of electrons and holes in the absorber layer. We used Triton-X100 as a hole transfer layer to transfer electrons and holes from the absorber layer to the anode and cathode. We showed that AuNPs enhance solar cells' current density and efficiency by increasing the light absorbance.

Our results showed that the Au/(Photosystem + Triton X-100 + GNP)/FTO sample exhibited the most promising photovoltaic behavior at standard conditions. The JSC, cut-off voltage, fill factor, and efficiency values converged to 0.099 mA/cm2, 0.107 V, 0.25, and 0.32%, respectively. We concluded that the Au nanoparticles bonded effectively to the pristine photosynthetic structure, facilitating charge transition in the photosynthetic solar cells. The results can illuminate hopes and dreams for biophotovoltaic solid-state solar cells with higher current density and higher efficiency.

In conclusion, our introduced synthesis process for biosolar cells could yield photovoltaic samples with acceptable efficiency and stability for actual applications.

In the future, for further investigation, we want to enter into the molecular dynamics of this issue.

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Declarations

Conflicts of interest/Competing interests

The authors declare no conflicts of interest.

Ethics Approval

Not Applicable

Not Applicable

Consent for Publication

Not Applicable

Authors' Contributions

Saeideh Golmohammadi, Designed the analysis, performed the study, and wrote the paper.

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