



# Article Green Hydrogen Generation from Eco-Friendly and Cost-Effective Red Sea Water Using a Highly Photocatalytic Nanocomposite Film, As<sub>2</sub>O<sub>3</sub>/Poly-3-methylaniline

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Abstract: The primary objective of this research is to address the energy challenges by introducing an innovative nanocomposite material. This material is designed to facilitate the conversion of environmentally friendly and economically viable Red Sea water into hydrogen gas. The ultimate goal of this work is to pave the way for the development of a practical device that can be employed within households and industrial settings to directly convert water into hydrogen gas. This novel nanocomposite material synthesized through oxidative polymerization comprises As<sub>2</sub>O<sub>3</sub> and Poly-3methylaniline (P3MA). This material possesses an extensive absorption range, spanning up to 700 nm, and features a bandgap of 1.75 eV, making it a promising candidate for use as a photoelectrode in green hydrogen production. The unique aspect of this setup lies in the utilization of Red Sea water, a natural sacrificing agent, as the electrolyte, rendering the process eco-friendly and cost-effective. When it is employed as a photoelectrode, this material exhibits high sensitivity to green hydrogen production, generating 6 moles/10 cm<sup>2</sup> h of hydrogen. At a voltage of -0.83 V, the current density values are measured as  $-0.08 \text{ mA} \cdot \text{cm}^{-2}$  (J<sub>ph</sub>) in light and  $-0.02 \text{ mA} \cdot \text{cm}^{-2}$  (J<sub>o</sub>) in darkness. Furthermore, the photoelectrode's responsiveness to light is assessed with different optical filters, revealing the optimal performance at 340 nm, where  $J_{ph}$  reaches  $-0.052 \text{ mA} \cdot \text{cm}^{-2}$ . These outcomes provide strong evidence of the photoactivity of the As<sub>2</sub>O<sub>3</sub>/P3MAphotoelectrode for green hydrogen production using Red Sea water. This underscores its potential for the development of an electrochemical cell for the direct conversion of sea water into H<sub>2</sub> gas.

Keywords: poly-3-methylaniline; As<sub>2</sub>O<sub>3</sub>; Red Sea water; green hydrogen; photoelectrode

# 1. Introduction

The main reasons for producing clean energy that is not harmful to the environment are the global energy crisis and environmental challenges. Especially due to increased pollution, which has begun to instill fear, and the decline of fossil fuels, the demand for clean energy has increased. Much of the world's power is sourced from fossil deposits, which has a major role in the pollution of layers of the atmosphere, causing the phenomenon of global warming [1–3]. H<sub>2</sub> gas is the cheapest and most widely applied renewable energy source. Through photocatalysis, scientists can produce H<sub>2</sub> from various electrolytes: bases, acids, and neutral mediums [4,5]. In addition, many companies and factories use this gas as an alternative fuel to fossil fuels. The less fossil fuels are used, the less dangerous the gas emissions will be, such as carbon dioxide, nitrogen, and sulfur oxides. H<sub>2</sub> gas is also characterized by its combustibility and good performance [6,7]. But the generation



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). of  $H_2$  gas as a clean and renewable fuel requires stable and sufficient photocatalysts in the future.  $H_2$  gas can be an alternative to fossil fuels as an energy source [8]. Hydrogen is produced via the electrolysis of water, and this process requires an electrical voltage greater than 1.23 V to produce H gas due to slow oxygen reactions [9,10]. In 1972, Fujishima and Honda invented the water-dispersion (PWS) photocatalytic method using ultraviolet light for the first time. Next, the researchers produced H gas using photocatalysts and semiconductors. The production of H gas via photocatalysis and direct water dispersion is a good method and can give a solution to the current energy shortage [11,12]. The light reactions applied to generate H<sub>2</sub> gas are performed on metal sulfide, oxides, or polymer semiconductor materials that have a great optical performance and additional commercial advantages, such as, they can be mass produced or have low costs [13]. To increase the production of H<sub>2</sub>, these selected materials are favorable to have a large surface area that reflects the number of active sites, so that the nanomaterials, nanowires, or sheets are ready for the  $H_2$  generation process [7,14–16]. The photocatalytic interactions of semiconductors show prominent photocatalytic water scattering activity. However, the photocatalytic degradation and rapid recombination of the photocatalyst have reduced the appreciable applications of photocatalytic  $H_2$  gas production. To solve this problem, many types of applications have been proposed. For example, carbon-based materials, noble metals, and nonmetals as well as homo- and hetero-structures are doped using transition metal oxide polymers into interchangeable metal-substitutable compounds, especially in electronic devices [17,18]. The primary goal of the researchers in developing these polymers is to reach an optimal band vacuum of 1.2 to 1.5 eV, which is achieved through the induction of photon capture inside the molecular texture of these materials. This development is illustrated by the nanoformulation and composite using additives that have a wide range of light responses. There are some studies conducted on polymer compounds to disperse water and generate  $H_2$  gas. Some studies have worked on the PANI composite with  $TiO_2$ through testing their photocatalytic performance from a water solution, and the produced  $J_{ph}$  value has a limited performance [19]. Also, there are additional previous studies on using polymer composites for hydrogen production, but these studies depended on using an acid medium, such as  $H_2SO_4$  or HCl as an electrolytes, and the generated  $J_{ph}$  values were very limited. Some of these materials are polyaniline/MoS, Ni/polyaniline, and poly(3-aminobenzoic acid) frameworks [19–21].

This study introduces a new photoelectrode for producing green hydrogen using Red Sea water, which is both environmentally friendly and cost-effective. The  $As_2O_3/P3MA$  photoelectrode is thoroughly characterized after its preparation, and its excellent absorption and small bandgap make it ideal for hydrogen generation. The sensitivity of the photoelectrode is evaluated using a three-electrode cell and optical filters to adjust the light frequency. The amount and rate of hydrogen gas production are determined based on  $J_{ph}$  and  $J_0$  values.

#### 2. Experimental Details

#### 2.1. Characterization and Materials

m-Toluidine and sodium arsenite (NaAsO<sub>2</sub>) were obtained from Merck, Rahway, NJ, USA, dimethylformamide (DMF) and silver paste were obtained from Sigma Aldrich, Saint Louis, MO, USA, and Na<sub>2</sub>S<sub>2</sub>O<sub>8</sub> was obtained from Pio-Chem, Cairo, Egypt.

The characterization of materials was carried out using various analytical techniques. XRD (PANalytical) was used for confirming the chemical composition by analyzing 2 theta degrees. XPS (Kratos, UK) was performed to understand the elemental composition of the materials by analyzing the electron photon phenomenon. FTIR (Bruken) was applied to determine the function groups of the materials. SEM (ZEISS) was used to determine the 3D topography of the material, while TEM (JEOL) was used for 2D morphology confirmation. Additionally, the absorbance of the materials was determined using a Perkin Elmer spectrophotometer device, and the bandgap was calculated using the Tauc equation.

## 2.2. Preparation of P3MA and As<sub>2</sub>O<sub>3</sub>/P3MA

P3MA and  $As_2O_3/P3MA$  nanocomposites were prepared using the same technique, which involves adding the oxidant suddenly (fast addition) to the monomer dissolved in HCl acid at 25 °C. In terms of adding the oxidant to the monomer, the process involves a rapid, one-step addition of the oxidant solution to the monomer solution. This swift addition promotes the formation of nanopolymer, effectively preventing the formation of large granules. The oxidant used for the monomer was  $K_2S_2O_8$ , while for  $As_2O_3/P3MA$ , it was a combination of 0.12 M  $K_2S_2O_8$  and 0.15 M NaAsO<sub>2</sub>. The monomer used in both reactions was 0.06 M 3-methylaniline, which dissolved in 0.5 M HCl under stirring for 30 min in atotal solution of 100 mL. The polymer obtained from the reaction was then collected using the centrifugation method after one day, purified, and dried at 60 °C thoroughly.

#### 2.3. The Hydrogen Generation System

The process of hydrogen generation was conducted using Red Sea water as the naturally occurring electrolyte, eliminating the need for any additional electrolytes. This electrochemical reaction was facilitated within a three-electrode cell configuration, which included the  $As_2O_3/P3MA$  nanocomposite film as the primary electrode, graphite serving as the auxiliary electrode, and a calomel electrode fulfilling the role of the third electrode.

To quantify the production of hydrogen gas during this process, a specialized device known as the CHI608E was employed. This device is capable of measuring and recording important parameters, particularly the current density under both light and dark conditions. Under illumination, the device records a current density denoted as J<sub>ph</sub>, representing the photo-induced current density. This parameter is crucial for assessing the efficiency of hydrogen generation in the presence of light, which could be derived from various sources, including natural sunlight or artificial illumination.

In the absence of light, the device records another current density labeled as J<sub>o</sub>, representing the dark current density. This measurement provides insights into the hydrogen generation process when no external light source is present. Understanding the dark current density is important as it allows the assessment of hydrogen production efficiency in conditions where illumination is not a factor, helping to distinguish between photo-induced and non-photo-induced contributions to the overall current.

The CHI608E device, with its ability to monitor current density under both illuminated and non-illuminated conditions, plays a crucial role in characterizing the effectiveness of the hydrogen generation reaction in Red Sea water using the  $As_2O_3/P3MA$  nanocomposite film electrode. These data are essential for evaluating the performance and potential applications of the hydrogen generation process, particularly in environmentally relevant and sustainable contexts. The optical filters were inserted for controlling the light wavelengths using a metal halide lamp. The hydrogen generation system is shown in Figure 1.



Figure 1. The schematic diagram of the hydrogen generation system.

### 3. Results and Discussion

## 3.1. Analyses

The XRD pattern of P3MA and  $As_2O_3/P3MA$  (Figure 2a) was determined through the diffraction angles at which the X-rays constructively interfered with each other after interacting with the crystal lattice. Through this interaction, the P3MA has abroad bands at  $15^{\circ}$  confirms the amorphous behavior of this prepared polymer; this matched well with the aniline derivate polymers.



**Figure 2.** (a) X-ray pattern and (b) FTIR spectroscopy of P3MA and  $As_2O_3/P3MA$  nanocomposite. XPS spectra survey of (c)  $As_2O_3/P3MA$  nanocomposite and (d)  $As_3d_{3/2}$  (brown) and  $As_3d_{5/2}$  (red) spectra.

However, the emergence of distinct peaks at  $21^{\circ}$  and  $24.6^{\circ}$  signifies the establishment of crystalline characteristics within the composite material. This crystalline nature is attributed to the chemical bonding interactions formed between P3MA and the inorganic As<sub>2</sub>O<sub>3</sub>, resulting from the incorporation of oxide within the polymer matrix [22]. The XRD pattern also shows sharp peaks related to As<sub>2</sub>O<sub>3</sub> [23] at 26.5°, 28.5°, 31.7°, 34.4°, and 45.4°, which allowed the calculation of the crystalline size (D) using Scherrer's equation (Equation (1)) [24]. By using the strongest peak at 34.4° and the full width half maximum value, the calculated D value was found to be 22 nm.

$$D = 0.9\lambda/W\cos\theta \tag{1}$$

The FTIR spectroscopic analysis data of both P3MA and the  $As_2O_3/P3MA$  composite are presented in Figure 2b. In the FTIR spectra of P3MA, several distinctive bands were observed, each corresponding to specific chemical groups and functional bonds within the molecule. Firstly, the bands observed at wavenumbers 3406 cm<sup>-1</sup> and 2915 cm<sup>-1</sup> are indicative of certain functional groups. The band at 3406 cm<sup>-1</sup> is associated with N-H, suggesting the presence of amino (N-H) groups in the P3MA structure. Meanwhile, the band at 2915 cm<sup>-1</sup> corresponds to C-H, indicating the presence of carbon–hydrogen (C-H) bonds in the molecule. Another noteworthy feature in the FTIR spectra of P3MA is the band at 1727 cm<sup>-1</sup>. This band is assigned to N-H, which further emphasize the presence of amino groups within the P3MA compound. Additionally, two distinct bands are observed at 1640 cm<sup>-1</sup> and 1529 cm<sup>-1</sup>, which can be attributed to the vibrations of the C=C and C-N bonds, respectively. These bands signify the presence of double carbon–carbon (C=C) bonds and carbon–nitrogen (C-N) bonds in the molecular structure of P3MA. Lastly, the FTIR spectrum of P3MA reveals a band at 1370 cm<sup>-1</sup>, which is associated with the stretching vibrations of the C-N bond. This particular bond is characteristic of amine groups, further confirming the presence of nitrogen-containing functional groups in P3MA.

These bands are attributed to the presence of P3MA in the composite. In the case of the  $As_2O_3/P3MA$  composite, there are a few new observed bands, indicating the chemical reaction between  $As_2O_3$  and P3MA. However, there are little shifts in some band positions, indicating that there is some interaction between the two materials. The band at 3406 cm<sup>-1</sup> represents the N-H stretching vibration of P3MA, which shows a shift towards a higher wavenumber (3410 cm<sup>-1</sup>), indicating the interaction of N-H with  $As_2O_3$ . The band at 1640 cm<sup>-1</sup> is for the C=C vibration, showing a shift towards a lower wavenumber (1602 cm<sup>-1</sup>) [25], indicating the interaction of C=C with  $As_2O_3$ . These shifts in the band positions confirm the presence of  $As_2O_3$  in the composite, as well as its interaction with P3MA.

To further analyze the elemental structure of the As<sub>2</sub>O<sub>3</sub>/P3MA composite, XPS analyses were conducted, and the results are shown in Figure 2c,d for the composite and As elements, respectively. The pure P3MA polymer exhibited characteristic peaks in the 1s spectra at 400 and 285 eV, corresponding to the N and C elements, respectively [26]. Additionally, the presence of HCl in the acid medium used during synthesis led to an enhancement in the conductivity of the polymer, as indicated by the peak for Cl element at 199 eV.

The presence of  $As_2O_3$  as an inorganic filler within the polymer matrix was confirmed by examining the  $As_3d_{3/2}$  spectrum (44.3 eV, depicted by the brown curve) and the  $As_3d_{5/2}$ spectrum (45.4 eV, represented by the red curve). These spectra clearly indicate that the oxidation state of arsenic (As) is III. Furthermore, the intense peak observed at 532 eV in the O1s spectrum provides further confirmation of the presence of  $As_2O_3$  compound within the composite.

The amount of light absorbed by a material over a given distance is referred to as optical absorbance, and it is illustrated in Figure 3a for P3MA (black curve) and As<sub>2</sub>O<sub>3</sub>/P3MA composite (red curve). P3MA displays good absorbance at 370 and 600 nm, whereas the formation of As<sub>2</sub>O<sub>3</sub>/P3MA exhibits a broad optical absorbance that extends to about 800 nm due to the incorporation of As<sub>2</sub>O<sub>3</sub> within the P3MA chains. This significant absorbance covers a wide optical range, extending to the IR region. The band gap of the composite is calculated to be 1.75 nm using the Tauc equation (Equation (2)) [27,28], as indicated in Figure 3b, indicating an ideal band gap. We used the absorbance coefficient ( $\alpha$ ), frequency ( $\nu$ ), and plank constant (h) for this evaluation. Therefore, this composite holds a promising potential for optical applications, such as solar cell layers or optoelectronic light sensing [29,30].

$$(\alpha h\nu)^{0.5} = A(h\nu - Eg)$$
<sup>(2)</sup>

The morphologies of P3MA and  $As_2O_3/P3MA$  nanomaterials were examined using SEM analysis, as depicted in Figure 4b, respectively. The formation of the composite resulted in a significant change in morphology, accompanied by improvements in the chemical and optical properties [31]. The compact nanofiber structure observed in the nanocomposite indicates enhanced crystallinity and optical behavior [32]. These nanofibers are composed of numerous particles that are in contact with each other and elongated together, leading to an increase in their overall length. In contrast, the nonuniform morphology of P3MA reflects its limited properties. This behavior is well demonstrated in the TEM image (Figure 4c), where interconnected particles form the As<sub>2</sub>O<sub>3</sub>/P3MA nanocomposite. Furthermore, roughness analysis using the Gwydion theoretical program (Figure 4e) confirms the formation of

compacted nanofibers that are tightly interconnected. Conversely, Figure 4d shows noncompacted particles with a nonuniform distribution in the P3MA sample.



Figure 3. (a) Optical (b) the energy band gap for of As<sub>2</sub>O<sub>3</sub>/P3MA (red curve) and P3MA (black curve).



Figure 4. SEM of (a) P3MA and (b)  $As_2O_3/P3MA$  nanocomposite. (c) TEM of  $As_2O_3/P3MA$  nanocomposite. Theoretical modeling: cross section and roughness of (d) P3MA and (e)  $As_2O_3/P3MA$  nanocomposite.

#### 3.2. Red Sea Water (Electrolyte) for Hydrogen Generation: The Electrochemical Study

The concentrations of heavy metals in the electrolyte used for hydrogen generation in this electrochemical study are presented in Table 1, and they are derived from Red Sea water. The  $J_{ph}$  values were evaluated under different light conditions to investigate the sensitivity of the  $As_2O_3/P3MA$  composite photoelectrode to light photons. When the photoelectrode is illuminated, hot electrons are generated, which then migrate to the Red Sea water for an electrochemical reaction that results in the splitting of the water molecules. This electrochemical study was conducted using the CHI station to measure the current–voltage or current–time relations. Overall, these studies aimed to explore the potential of the  $As_2O_3/P3MA$  composite photoelectrode for efficient photoelectrochemical water splitting.

Heavy Metal	Conc. (mg/L)
В	0.132
Pb	0.008
Zn	0.044
Ni	0.001
Cr	0.005
Mn	0.009
Cd	0.001
Cu	0.10
Fe	0.012
Cd Cu Fe	0.001 0.10 0.012

Table 1. The Red Sea water with metal concentrations [33].

The  $As_2O_3/P3MA$  composite photoelectrode showed a higher rate of hydrogen generation under light (Figure 5a) compared to the Jo value in the dark. This suggests that a photocatalytic reaction occurred on the surface of the As<sub>2</sub>O<sub>3</sub>/P3MA composite under light illumination. The bandgap of this composite is 1.75 eV, which is smaller than the UV or visible light range. This indicates that the transfer of electrons occurs easily under these light regions, forming an electron cloud on the surface of the photoelectrode [34]. In the presence of sea water, these electrons find their way to the solution, where the heavy metal plays the role of a sacrificing agent to promote the splitting reaction. The difference in J<sub>ph</sub> and J<sub>o</sub> values of -0.08 and -0.02 mA·cm<sup>-2</sup> at (-0.83 V), respectively, is an indication of this process. The smooth light curve suggests a Schottky barrier reaction [35,36], indicating the generation of electrons under light illumination. For the P3MA under light illumination, in the presence of light, the  $J_{ph}$  value exhibits a notable increase, reaching  $-0.028 \text{ mA} \cdot \text{cm}^{-2}$  at -0.83 V. This enhanced response signifies the heightened sensitivity of this pure polymer to incident photons of light, which induce electron transitions at higher energy levels, specifically the LUMO (Lowest Unoccupied Molecular Orbital). This behavior underscores the semiconducting characteristics of this promising polymer. The smallest J<sub>o</sub> value represents the self-current of the  $As_2O_3/P3MA$  composite due to its semiconductive nature.

Figure 5b shows the current density–time (J-t) curves of the  $As_2O_3/P3MA$  composite photoelectrode under chopped light illumination. The up and down behaviors of the J values represent the sensitivity of this photoelectrode under both dark and light conditions at limited bias potential values. The positive current value in dark conditions represents the self-current of the photoelectrode due to its semiconductive nature [37,38]. The negative current values under light conditions indicate a photocatalytic reaction on the surface of the composite under the motivation of incidence light. The negative bands represent the transfer of electrons to the sea water and the consequent hydrogen gas production. The smooth curves between the peaks represent the Schottky barrier reaction that gives an indication of the generation of electrons under light motivation [35,39–41]. The remarkable durability of the metal oxide materials encapsulated within the P3MA matrix significantly enhances the stability and consistency of the  $As_2O_3/P3MA$  composite, as depicted in Figure 4b. Furthermore, the composite's resistance to corrosion and its inherent semiconductor properties play a pivotal role in ensuring its repeatability and reliability. Overall, these results demonstrate the potential of the  $As_2O_3/P3MA$  composite photoelectrode for hydrogen generation with high sensitivity to light illumination.



**Figure 5.** The produced  $J_{ph}$  and  $J_0$  values under light and dark conditions, respectively, through the (a) current–voltage and (b) current–time relations.

The sensitivity of the photoelectrode to light frequency was estimated by illuminating the  $As_2O_3/P3MA$  composite photoelectrode surface with different photon wavelengths and measuring the resulting  $J_{ph}$  values, as shown in Figure 6a. The frequency of light is represented by the different wavelengths of 340, 540, and 730 nm, with increasing energy associated with smaller wavelengths from 730 to 340 nm. This resulted in an increase in  $J_{ph}$  values in the direction of the decreasing wavelength, with the optimum value at 340 nm being  $-0.052 \text{ mA} \cdot \text{cm}^{-2}$ , as depicted in Figure 6b. The increase in  $J_{ph}$  values under high-frequency light is normal and represents greater electron transfer with increasing photon energy [42–44]. A notable aspect of this study is the potential commercial application of the prepared photoelectrode for  $J_{ph}$  generation under a wide optical region, enabling the conversion of Red Sea water to hydrogen gas using a three-electrode cell, which is consistent with previous studies by Rabia et al. [45–48].

Photocathodes are essential components in various optical and electronic devices, thanks to their remarkable efficiency in converting incident photons into electrons. What sets these photocathodes apart is their exceptional performance across a wide optical spectrum, spanning from the UV to IR wavelengths. This broad range of operation allows photocathodes to harness the entire spectrum of light, particularly excelling in the Vis and IR regions. The key to this impressive versatility lies in the unique properties of the composite materials used in the photocathode. These materials have a small bandgap, which measures at just 1.75 eV. This small bandgap significantly influences the energy of the incident photons that interact with the photocathode's surface, as described by the famous Einstein Equation,  $E = mc^2$ .



**Figure 6.** (a) The response of  $As_2O_3/P3MA$  photoelectrode for various frequency light (current voltage) (b) the  $J_{ph}$  values at -0.83 V.

Let us explore how this relationship between the bandgap and incident photon energy works in practice. At a wavelength of 730 nm, the energy of the incident photons is calculated using the Einstein Equation. This yields an energy value of 1.81 eV. This energy exceeds the photocathode's small bandgap of 1.75 eV. Transitioning to a shorter wavelength of 540 nm, the energy of the incident photons increases, and it measures at 2.3 eV. Again, this energy surpasses the photocathode's bandgap, ensuring efficient photon-electron conversion. Moving further into the ultraviolet spectrum, at a wavelength of 340 nm, the energy of the incident photons rises substantially to 3.6 eV. As expected, this energy comfortably exceeds the 1.75 eV bandgap of the photocathode material. These calculations exemplify the remarkable capacity of the photocathode to absorb a wide range of photon energies, making it efficient not only in the visible spectrum, but also in the ultraviolet and infrared regions. This adaptability is invaluable for a variety of applications, such as photodetectors, image sensors, and photomultiplier tubes, where capturing a broad range of light wavelengths is crucial. Moreover, the capability of the photocathode to harness photons with energies higher than its bandgap allows the generation of free electrons, which can be subsequently utilized in various electronic devices. This photocathode's ability to efficiently convert photons into electrons across this broad optical spectrum is of immense importance in scientific research, industrial applications, and even in everyday technologies like digital cameras and night-vision devices.

The incident photons, owing to their ample energy, can readily instigate the formation of electron–hole pairs within the energy levels of the composite materials. This initial step sets in motion the separation of electrons and holes, culminating in the liberation of high-energy electrons. These liberated electrons subsequently engage with neighboring solutions to facilitate the production of hydrogen gas. Within this intricate series of chemical and physical processes, the generated J<sub>ph</sub> values assume a pivotal role as a vital metric for assessing the overall efficiency of the reaction.

To delve deeper into this complex process, let us break down and elaborate on each of its key components. Photon Energy Initiation: The incident photons, with their substantial energy levels, play a pivotal role in triggering the reaction. When they strike the photocathode, they carry enough energy to excite electrons within the composite materials. This excitation leads to the creation of electron–hole pairs within the material. Electron–Hole Pair Separation: Following the creation of electron–hole pairs, these charged entities are separated due to the internal properties of the photocathode material. Electrons are liberated from their respective holes, and this process is crucial for enabling subsequent chemical reactions. The Release of High-Energy Electrons: The liberated electrons, often referred to as "hot electrons" due to their elevated energy levels, are released from the photocathode. These high-energy electrons are primed for further interaction with neighboring solutions.

Hydrogen Gas Generation: In the presence of these liberated high-energy electrons, a chemical reaction is initiated, which leads to the generation of hydrogen gas. These electrons act as catalysts, facilitating the reduction of protons ( $H^+$  ions) to produce molecular hydrogen ( $H_2$ ) from water or other suitable reactants. J<sub>ph</sub> Values as Efficiency Indicators: Throughout this intricate sequence of events, the generated J<sub>ph</sub> values are of paramount significance. J<sub>ph</sub>, or the photocurrent, represents the flow of electric current produced as a result of photon absorption and electron liberation. It serves as a critical indicator of the overall efficiency of the reaction. Higher J<sub>ph</sub> values indicate the more efficient conversion of incident photons into useful electrical or chemical energy.

In practical terms, the ability of the photocathode to efficiently create electron–hole pairs and release high-energy electrons is central to its performance in applications such as photocatalysis for hydrogen generation. The use of hot electrons as catalysts in the production of hydrogen gas offers a sustainable and environmentally friendly approach to fuel production. This process can be applied using renewable energy technologies, offering a promising avenue for clean hydrogen production.

In summary, the incident photons' energy initiates a chain of events, including the creation of electron–hole pairs, the separation of electrons and holes, the release of high-energy electrons, and the subsequent generation of hydrogen gas. The assessment of  $J_{ph}$  values is crucial for evaluating the efficiency of this reaction, with higher values indicating the more effective utilization of incident photons for the desired output, making it a key parameter in the realm of sustainable energy and catalysis.

The efficiency of the photoelectrode for hydrogen gas production can be reflected by calculating the moles of hydrogen gas generated during the splitting of Red Sea water (Figure 7). The Faraday law can be used to calculate the moles of substance, which is given by the formula: moles of substance = (electric current  $\times$  time)/(Faraday's constant  $\times$  number of electrons transferred in the reaction) [49]. The estimated moles of H<sub>2</sub> generated using the As<sub>2</sub>O<sub>3</sub>/P3MA composite photoelectrode is 6 moles/10 cm<sup>2</sup>·h, which is a significant amount for production of H<sub>2</sub> gas from sea water without the use of any external electrolytes.



Figure 7. The estimated hydrogen moles through the As<sub>2</sub>O<sub>3</sub>/P3MA nanocomposite photoelectrode.

## 4. Conclusions

A highly optical  $As_2O_3/P3MA$  nanocomposite with a 1.75 eV bandgap is prepared via oxidative polymerization using NaAsO<sub>2</sub> and K<sub>2</sub>S<sub>2</sub>O<sub>8</sub>. Due to its great absorption behavior in a wide optical range up to 700 nm, this composite is promoted as a photoelectrode for green hydrogen production.

The Red Sea water electrolyte is used as a hydrogen source, and the heavy metals work as a natural sacrificing agent for water splitting. This  $As_2O_3/P3MA$  photoelectrode shows a great sensitivity for green hydrogen, with 6 moles/10 cm<sup>2</sup>·h of hydrogen production. The great sensitivity of this photoelectrode is proved by the fact that the J<sub>ph</sub> and J<sub>o</sub> values are -0.08 and -0.02 mA.cm<sup>-2</sup> at (-0.83 V), respectively. Under testing this photoelectrode in various light frequency spectra using optical filters, the J<sub>ph</sub> has an optimum value at 340 nm of -0.052 mA·cm<sup>-2</sup>. This light sensitivity confirms the photoactivity of the fabricated  $As_2O_3/P3MA$  photoelectrode for green hydrogen using free Red Sea water. Moreover, this study is a promising for future studies on designing an electrochemical cell for the direct conversion of the Red Sea water into H<sub>2</sub> fuel.

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