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Original Research Article

Structure-Dependent Performance of N-Doped TiO_2 Nanowires toward Efficient Solar-Driven Hydrogen Production

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Abstract

This research focuses on enhancing hydrogen production via the photocatalytic method using a TiO_2 catalyst with nitrogen doping and morphology modification to improve efficiency. Nitrogen-doped TiO_2 nanowires (NTN) were successfully hydrothermally grown on titanium foil to produce thin-film photocatalysts for the visible-light-driven production of hydrogen. Nitrogen incorporation induced bandgap narrowing, from 3.18 eV to 2.85 eV, by introducing N 2p states close to the valence band, thereby increasing visible-light absorption. Structural analyses confirmed the formation of lattice strain and oxygen vacancies associated with substitutional doping, while the one-dimensional nanowire architecture enhanced charge transport and reduced carrier recombination pathways. The optimized N–TiO_2 NWs demonstrated the highest hydrogen evolution rate of 2.385 µmol/cm^2 under 180 minutes of visible-light irradiation, corresponding to a hydrogen evolution rate of 0.795 µmol/cm^2/h, without a noble-metal co-catalyst. A strong correlation is established between nitrogen-induced surface electronic modification and the enhancement of nanowire-driven charge separation. This study presents a recyclable and scalable thin-film photocatalyst design suitable for future solar hydrogen production systems.

Keywords: TiO_2 nanowires; chitosan; photocatalytic; photoproduction of hydrogen (H_2)

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1. Introduction

There are many factors that cause environmental damage, including carbon-based energy production like fossil fuels and rapid industrialization. Currently, fossil fuels remain the world's largest source of energy, accounting for approximately 75%. The world energy consumption is also predicted to increase by 49% over the next 20 years, along with the increasing growth of the world's population. However, the use of fossil fuels is known to produce greenhouse gas emissions, exacerbating climate change and global warming [1,2]. On the other hand, high concentrations of organic and inorganic compounds in liquid waste produced by the textile industry also cause a decrease in water quality [3]. Therefore, rapid economic growth and industrial development can cause problems in the form of increasing environmental pollution and global energy demand [1,3].

Investigating renewable energy sources is an essential step to address energy security and environmental concerns, because the current supply of fossil fuel resources is also dwindling

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[1,2]. To address these problems, it is necessary to shift toward alternative and sustainable energy sources, one of which is hydrogen, which can be used as a clean energy carrier for industrial and transportation applications [2,4]. Hydrogen is an environmentally friendly fuel, produces high energy in its application, and has distinct benefits over conventional fuels [2,5,6]. Its applications span across electric vehicles, aviation, and industrial sectors, positioning hydrogen as a strategic replacement for fossil fuels and a key enabler of sustainable energy practices [7]. The demand for hydrogen fuel is rapidly increasing, and projections indicate that it could meet up to 18% of the global energy demand by 2050, underscoring its critical role in the future energy landscape [8].

Hydrogen can be obtained through various methods, including electrolysis, biological processes, and photocatalysis. Among these, the photocatalysis method has the benefit of converting light energy into hydrogen in a more environmentally friendly way [9]. Photocatalysis is a process that involves photochemistry and catalysts/semiconductors, where the catalyst is triggered by photons that affect the speed of chemical reactions. The rational selection and design of semiconductors play a significant role in photocatalytic hydrogen production [10]. Therefore, developing visible-light photocatalysts has become crucial to achieve highly efficient hydrogen production. This is because the solar spectrum contains around 46% visible light. Catalysts with a lower energy band gap are more efficient for water splitting. Over the past few decades, extensive research has focused on finding optimal catalysts for solar-promoted hydrogen production [11].

Several transition metal semiconductors, such as $BiVO_4$, WO_3, ZnO, MgO, and TiO_2, have photocatalytic capabilities [1,9]. From all of these semiconductors, titanium oxide (TiO_2) is one of the superior semiconductor materials in the photocatalysis process to produce hydrogen. TiO_2 has several advantages as a photocatalyst, including cost-effectiveness, environmental friendliness, stability, non-toxicity, and photoactivity [1,9,10,12]. However, the efficiency of TiO_2 is limited by several disadvantages, such as a wide band gap (3.0-3.2 eV), which results in a narrow light adsorption range that accounts for only about 5% of the solar spectrum, as well as rapid recombination of photogenerated electrons and holes, thereby reducing its efficiency. Various strategies have been developed to overcome these disadvantages of TiO_2 and improve its photocatalytic efficiency, including changing its morphology and doping with metal or non metal elements [10].

Nitrogen is one of the most effective dopants for TiO_2 due to the comparable energy level of its 2p orbitals to the O 2p valence band. Introduction of nitrogen into the TiO_2 lattice creates N 2p states above the valence band, resulting in enhanced photoexcitation under visible light. Moreover, nitrogen doping can generate oxygen vacancies which serve as charge carrier traps that minimize recombination losses. Despite these advantages, many doped TiO_2 photocatalysts remain in powder form, posing limitations such as particle agglomeration, catalyst recycling difficulties, and poor charge transport between particles [1,13,14]. Apart from that, changing the morphology into one-dimensional, such as nanowires, nanorods, and nanotubes, has also been reported to improve the photocatalytic activity of TiO_2. Wellia *et al.* have reported that TiO_2 with a nanowire morphology enhances photocatalytic activity in the photoreduction of Cr(VI) ions. It is explained that the nanowires' morphology increases the surface area of the catalyst, where the redox reactions occur during the photocatalytic process [15]. Additionally, nanowire architectures offer directional electron transport pathways along the axial direction, thereby reducing recombination through shortened diffusion distances. When immobilized as surface-grown thin films, nanowires offer additional benefits including mechanical stability, recyclability, and improved interfacial electron collection—important requirements for practical photocatalytic devices.

The modified TiO_2 can be achieved by various methods, one of which is the hydrothermal synthesis method. This method is one of the most common methods in synthesizing TiO_2 with one-dimensional nanostructures because of its easy and simple operation without needing templates [16]. The nitrogen source used is also considered an important factor in the synthesis. Various nitrogen compounds are used in the preparation of N-doped titania, one of which is chitosan, which is considered to produce an effective nitrogen-doping material [17]. Mahmoud *et al.* conducted research to compare the photocatalytic activity of TiO_2 and N-doped TiO_2 in reducing heavy metal ions Cr(VI). Mahmoud et al. used chitosan as a nitrogen source, as well as different morphologies. The results obtained showed that N-doped TiO_2 with chitosan as a nitrogen source showed the best photocatalytic activity results [18].

However, a knowledge gap remains in correlating nitrogen-induced electronic modification with the structure–performance relationship in thin-film nanowire systems for visible-light hydrogen evolution. Most studies focus either on powder-based photocatalysts or overlook the role of lattice strain and surface defect formation in enhancing charge transport. Therefore, this study focuses on synthesizing N-doped TiO_2 nanowires via hydrothermal method using chitosan as the nitrogen source to assess the effect and examine photocatalytic activity during hydrogen production (a renewable energy).

2. Materials and Method

The materials used in this research are titanium foil (Ti), chitosan, NaOH (Merck), glacial acetic acid (CH_3COOH), methanol (p.a Merck), deionized water, distilled water, acetone (C_3H_6O), and HCl (Merck). While the tools used during this research are glassware, analytical balance, magnetic stirrer, oven, furnace, autoclave, cylinder vessel, ultrasonicator, reactor, and a 50Watt LED lamp. Instruments used for sample characterization included X-Ray Diffraction (XRD), Scanning Electron Microscope-Energy Dispersive X-Ray (SEM-EDX), Fourier Transform Infra-Red (FTIR), and UV-Visible Diffuse Reflectance Spectroscopy (UV-Vis DRS).

Titanium foil with a thickness of 0.1 mm was cut into a size of 2 cm × 2 cm, then cleaned with an ultrasonicator in a mixed solution of ethanol, acetone, and deionized water with a volume ratio of 1:1:1 for 30 minutes. The titanium foil pieces were placed upright in a 50 mL Teflon-coated autoclave. For the first sample variation, 0.4 g of chitosan was added to Teflon and 40 mL of 1 M NaOH solution was added. After that, the autoclave was put into an oven at 220 ℃ for 48 hours, then the sample was removed and washed with deionized water several times, and then immersed in 0.6 M HCl for 60 minutes. After that, the samples were rewashed with deionized water and dried at room temperature. Next, the sample was calcined in a furnace at 500 ℃ for 1 hour. The resulting product was labelled NTN-1. The same steps were repeated for the addition of chitosan, with volumes of 0.8 g (NTN-2) and 1.2 g (NTN-3), to achieve a total volume of 40 mL for the chitosan plus NaOH solution. Meanwhile, the control used is a TiO_2 sample without the addition of chitosan, labelled as TN.

During the testing of photocatalytic activity, the TiO_2 film used is employed as a photocatalyst to produce hydrogen. Photocatalytic hydrogen production was evaluated using TiO_2 thin films grown on titanium foil (TN, NTN-1, NTN-2, and NTN-3). The photocatalyst films were cut into 1 × 1 cm pieces and placed in cylindrical quartz bottles containing a mixture of 20 mL deionized water and 5 mL methanol as a sacrificial agent. Prior to irradiation, the reactor bottles were purged with argon gas for 5 min to remove dissolved gases and create an inert atmosphere. The sealed reactors were irradiated under visible light using an Opsytec BS-02 photoreactor equipped with an Osram lamp 50 W and UV cut-off filter for 180 min. After irradiation, 0.5 mL of gas from the headspace was withdrawn using a gas-tight syringe and analyzed using gas chromatography (Shimadzu GC-2014) equipped with a thermal conductivity detector (TCD) and argon as the carrier gas. Hydrogen quantification was performed using the calibration response factor obtained from the instrument calibration. The hydrogen volume generated in the reactor was calculated using the following relation:

$$\frac{V\,Hydrogen,\,bottle}{V\,bottle\text{-}V\,liquid} = \frac{V\,hydrogen,\,sample}{V\,sample} \qquad (1)$$

where $V_{Hydogern,bottle}$ is the total hydrogen volume in the reactor bottle, V_{bottle} is the bottle volume, V_{liquid} is the liquid volume inside the bottle, $V_{Hydrogen,sample}$ is the hydrogen volume measured from the injected gas sample, and V_{sample} is the headspace gas volume collected for GC analysis (0.5 mL). The hydrogen production was then expressed as μmol/cm² based on the photocatalyst area.

3. Results and Discussion

Figure S1 (Supporting Information) shows the images of all samples after calcination. N-doped TiO_2 nanowires were synthesized using a one-step hydrothermal method by utilizing chitosan as a nitrogen source in the TiO_2 doping process. The photocatalyst was grown on the surface of titanium foil hydrothermally with the addition of an alkaline solution (NaOH), which acts as a catalyst [19]. In synthesizing TiO_2 through three stages, namely hydrothermal, ion exchange, and calcination. In the first stage, the titanium foil loses its metallic lustre and changes colour to grey. In hydrothermal, there is a reaction between nitrogen from chitosan and sodium titanate on the substrate surface. Then, immersion in HCl solution is carried out to replace Na^+ ions with H^+ to become hydrogen titanate [20]. From the ion exchange, the morphology of the sample and the physical appearance of the substrate remain unchanged. In the final stage, calcination is performed to convert hydrogen titanate into anatase TiO_2 crystals in the form of nanowires. After calcination, the Ti foil will change color to white on its surface [21]. As shown in Figure. S1, the comparison between Figure S1(a) before synthesis and Figure. S1(b-e) after synthesis shows a coating on the surface of the substrate. The coating on the surface is the resulting product, namely N-doped TiO_2 nanowires. From these three stages, it can be noticed through the synthesis process as follows:

$$2Ti + 2NaOH + 4H_2O \rightarrow Na_2Ti_2O_5.H_2O + 4H_2 \qquad (2)$$

$$Na_2Ti_2O_5.H_2O + 2HCl \rightarrow H_2Ti_2O_5.H_2O + 2NaCl \qquad (3)$$

$$H_2Ti_2O_5.H_2O \xrightarrow[1\,h]{500^{o}C} 2TiO_2 + 2H_2O \qquad (4)$$

Reaction (2) is the reaction of the crystal growth process through the hydrothermal method, while reaction (3) is the reaction of the ion exchange stage, and reaction (4) describes the reaction of the calcination stage. The three stages will produce products in the form of N-doped TiO_2 (NTN) in the form of nanowires on the surface of the substrate [22–24].

3.1. Structural Properties of N-doped TiO_2

Figure 1 shows the XRD diffraction patterns of the standard and samples. The diffraction patterns reveal that all samples are crystalline. The peak positions of the samples are well-matched with the tetragonal structure of TiO_2 anatase corresponding to the ICSD No. 9852. All samples showed typical peaks of TiO_2 at $2\theta = 25.3°$ and 48.02° that are associated with (101) and (200) planes, respectively, according to the standard [25]. Furthermore, diffraction peaks observed at $2\theta = 40.18°$, 53.23°, 70.77°, and 76.59° are consistent with the characteristic peaks of Ti according to the ICSD No. 43614, which can be attributed to the use of a Ti foil substrate during the synthesis process [23]. In addition, Figure. 1(ii) shows that the sample diffraction peak has shifted towards a larger diffraction angle. The slight shift of the diffraction peak toward higher angles may be associated with lattice distortion induced by nitrogen incorporation or defect formation within the TiO_2 structure. However, such peak shifts can also be influenced by factors such as crystallite size variation or structural strain. Therefore, the XRD results provide supportive evidence of structural modification rather than direct proof of nitrogen incorporation[26]. Similar peak shifts associated with lattice distortion and dopant incorporation have been reported in previous studies on N-doped TiO_2 systems [23,26]. Notably, no diffraction peaks corresponding to impurities such as NaCl or Na_2TiO_3 are detected, indicating that the synthesized product exhibits high purity [15].

The size of the synthesized TiO_2 and N-TiO_2 crystals can be calculated using the Debye-Scherrer equation by calculating the Full Width Half Maximum (FWHM). Based on these calculations, the crystal size of TiO_2 nanowires (TN) without the addition of chitosan is 20.82 nm. Meanwhile, the size of each N-TiO_2 nanowire (NTN) crystal ranges from 20.90 to 25.95 nm. The increase in crystal size after doping is caused by the nitrogen dopant, which has a larger atomic radius than oxygen. This can sharpen the XRD peak with an increase in growth rate and crystal size without affecting the crystal structure [26].

3.2. Vibrational Properties of N-doped TiO_2

The bond vibrations in the samples were observed with FTIR spectroscopy. Figure 2 shows the FTIR spectra of TN and NTN. The absorption peak at a wavenumber of ~500 cm^{-1} originates from the stretching vibrations of Ti-O-Ti and Ti-O. This peak shows the formation of metal oxide bonds in the TiO_2 lattice, which indicates the success of TiO_2 synthesis [13]. Moreover, the absorption peaks in the range of 3360-3395 cm^{-1} originate from the presence of hydroxyl groups due to the tensile vibration of Ti-OH. This band absorption band was also exhibited due to the bending vibrations of water molecules adsorbed on the substrate surface. These hydroxyl groups play a crucial role in the photocatalytic process. The absorption band observed in the range of 1640-1650 cm^{-1} is attributed to the bending vibrations of water molecules (H-OH) and N-H groups. In NTN-3, an absorption band at 1511 cm^{-1} is observed, corresponding to the Ti-N-Ti bond's tensile vibration. This band, which is clearly observed for the NTN-3 sample, suggests

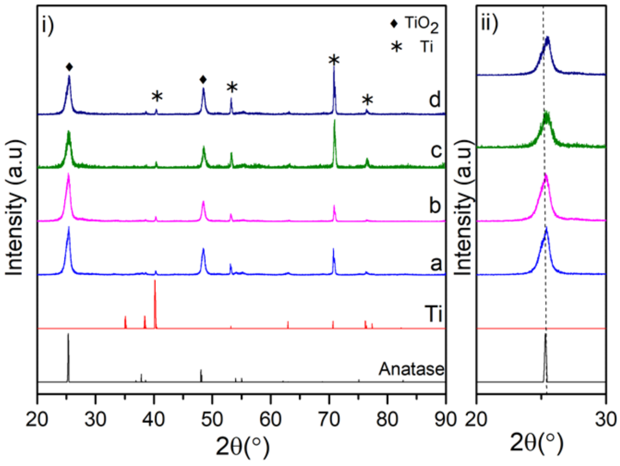

Figure 1. XRD measurement results of all samples: a) TN, b) NTN-1, c) NTN-2, d) NTN-3, and ii) Peak shift in the (101) plane.

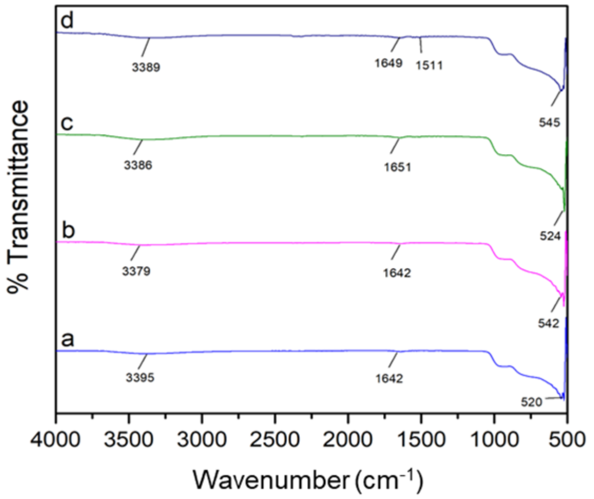

Figure 2. IR spectra of samples a) TN, b) NTN-1, c) NTN-2, d) NTN-3.

the formation of Ti–N related bonding, indicating nitrogen incorporation into the TiO_2 lattice. For the other NTN samples, nitrogen presence is supported by EDX analysis and optical bandgap modification observed in UV–Vis DRS spectra [26].

3.3. Morphology and Composition of N-doped TiO_2

The surface morphology of the N-TiO_2 nanowires (NTN) product can be determined through SEM measurements with 30,000 times magnification. Figure 3a shows the smooth surface of Ti foil before synthesis, which does not show any other morphological forms. Generally, the addition of NaOH to all samples provided the form of nanowire morphology [20], as shown in Figure 3. The formation and homogeneous growth of nanowires cover the smooth surface of Ti foil and are arranged randomly [27]. Meanwhile, the morphology of samples with the introduction of chitosan is shown in Figure. 3c-e. It is observed that NTN-2 has a nanorod morphology with a width of about 80 nm, while NTN-1 and NTN-3 have a nanowire morphology with a width of about 35 nm.

The elemental compositions of the samples were investigated using EDX analysis. As shown in Figure 4, all samples exhibited clear peaks for the elements titanium (Ti) and oxygen (O) in a 1:2 ratio, indicating that the formation of TiO_2 was successful. A nitrogen signal is observed in the EDX spectra of the NTN samples, indicating the presence of nitrogen in the synthesized materials. However, considering the limited sensitivity of EDX toward light elements, this result should be interpreted as supportive evidence of nitrogen presence rather than definitive proof of lattice substitution [28,29].

3.4. Optical Properties of N-doped TiO_2

The optical properties of NTN compounds are important in understanding the characteristics of photocatalytic properties in their application. Figure 5 shows the UV-Vis DRS spectra of all samples. The absorption of light by the TN sample shows that light absorption occurs at a wavelength below 400 nm (~380 nm). Notably, there is a slight shift in absorption intensity towards visible light (λ>400 nm). This confirmed that the light absorbance ability of modified NTN samples is considerably higher than that of the non-modified sample (TN). This is also attributed to the presence of doped nitrogen (N) element in TiO_2, as confirmed in the EDX analysis [28].

For further analysis, the bandgap energy of each sample was extracted through the Tauc plot method. By analyzing the relationship between

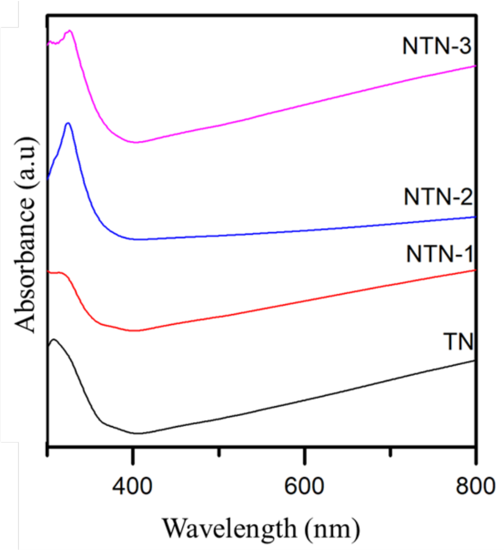

Figure 5. Absorbance value of a) TN, b) NTN-1, c) NTN-2, d) NTN-3.

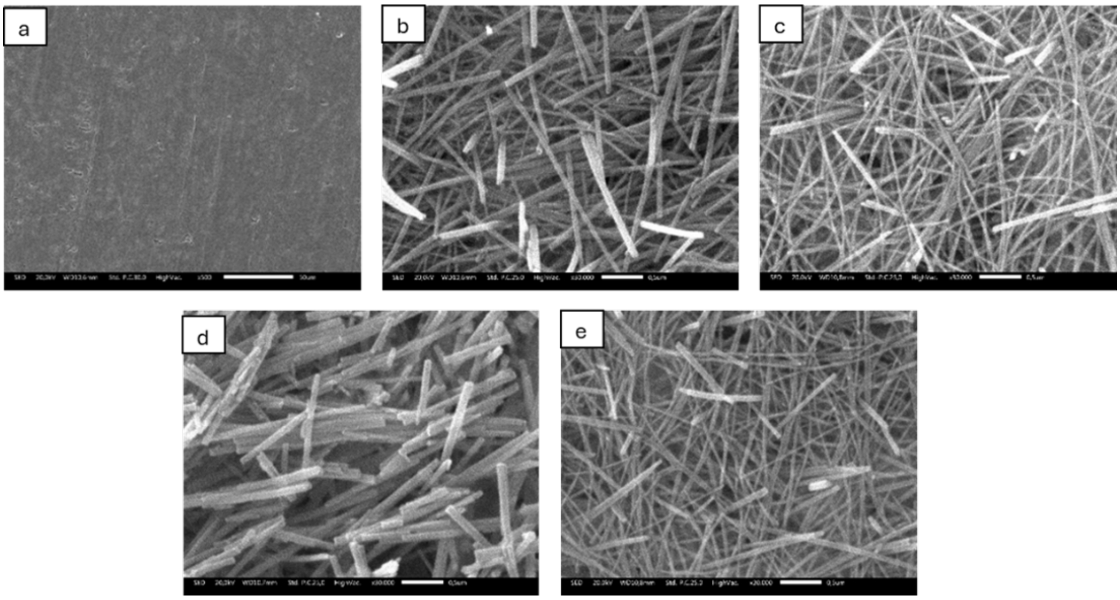

Figure 3. Morphological images of a) Ti foil, b) TN, c) NTN-1, d) NTN-2, and e) NTN-3.

the absorption coefficient and photon energy, the Tauc plot offers an effective approach for determining the optical bandgap, especially for materials with indirect transitions. It is commonly used in evaluating the electronic properties of semiconductors and photocatalysts. The TN sample exhibits a bandgap energy of 3.28 eV, as shown in Figure S2, which is higher than that of the NTN sample. In contrast, NTN-1, NTN-2, and NTN-3 samples exhibited band gaps of 3.21, 3.10, and 3.19 eV, respectively. This reduction is attributed to the influence of nitrogen content on TiO_2. Nitrogen induces the formation of an additional energy band close to the valence band of TiO_2, thereby narrowing the material's energy bandgap. This bandgap narrowing enhances the photocatalytic efficiency of TiO_2 [21].

3.5. Analysis of Photocatalytic Activity on Hydrogen Production

The photocatalytic activity of the material was observed through the hydrogen production rate of a water-methanol mixed solution under visible light irradiation. Figure 6 shows the photocatalytic activity of hydrogen production of all photocatalysts. TiO_2 with the addition of chitosan exhibits higher activity compared to pure TiO_2. The photocatalytic production rate of H_2 from TN, NTN-1, NTN-2, and NTN-3 samples was 0, 1.456, 2.385, and 1.722 µmol/cm², respectively. Based on the data in the bar chart, the NTN-2 photocatalyst performed the highest in H_2 production among other NTN photocatalysts. This result is consistent with the UV-Vis DRS characterization and bandgap energy calculations, which reveal that the NTN-2 sample has the lowest bandgap compared to the other photocatalysts. The reduced bandgap allows for more effective light absorption in the visible spectrum, directly contributing to the enhanced photocatalytic performance of the NTN-2 sample [30]. However, the photocatalytic activity trend

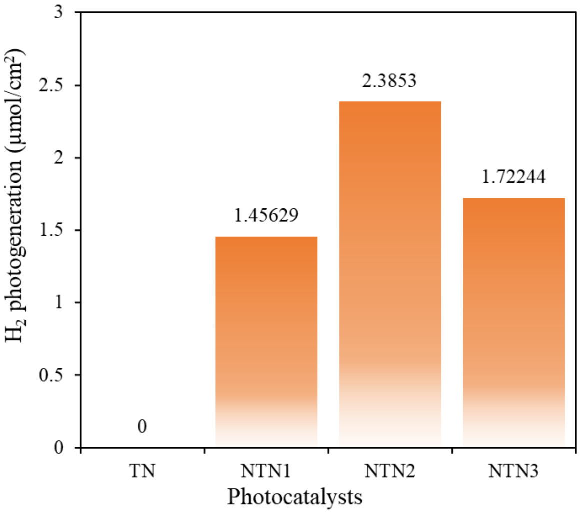

Figure 6. Hydrogen photoproduction results from all samples at 120 min.

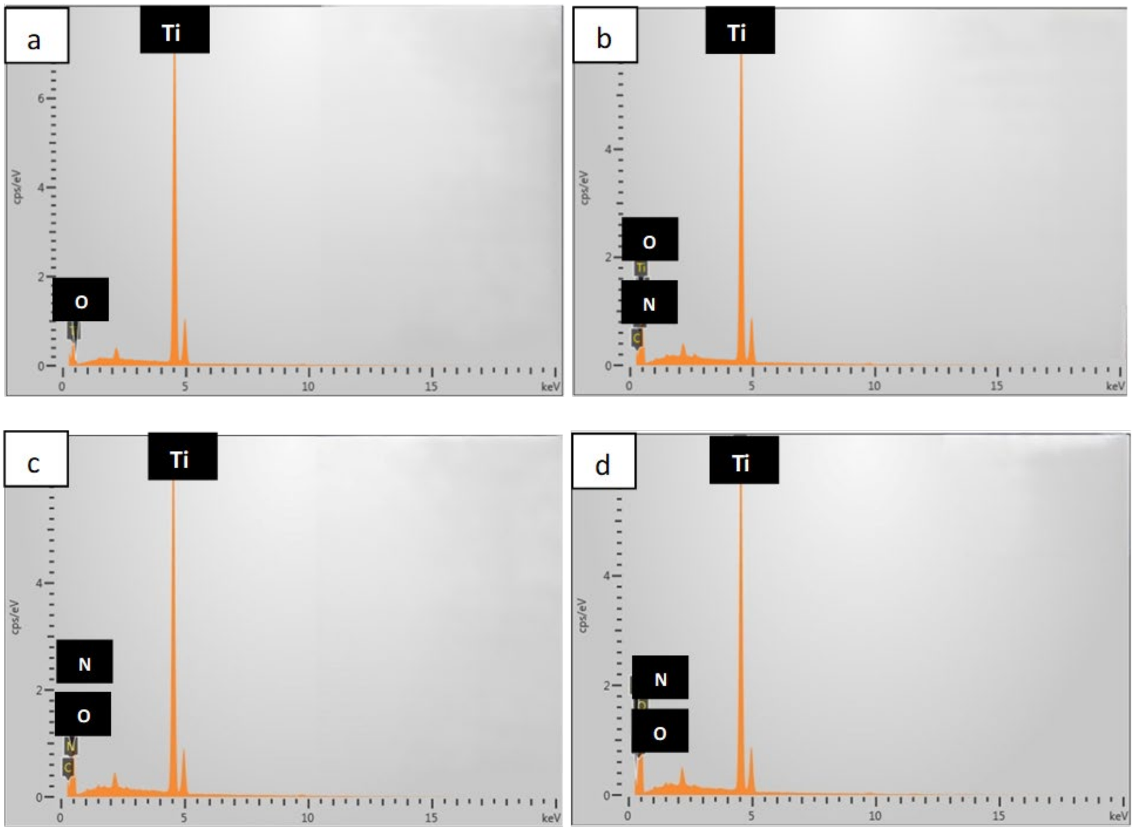

Figure 4. EDX spectra of a) TN, b) NTN-1, c) NTN-2, and d) NTN-3

among the NTN samples indicates that bandgap narrowing alone cannot fully explain the observed performance. Other physicochemical factors such as morphology, defect structure, and charge transport behavior also contribute significantly to the hydrogen evolution activity. SEM observations reveal that the morphology of the samples varies with the amount of chitosan added, where NTN-1 and NTN-3 predominantly exhibit nanowire structures, while NTN-2 tends to form thicker nanorod-like structures. One-dimensional TiO_2 nanostructures are known to facilitate directional charge transport along their axial direction, which can reduce electron–hole recombination and improve photocatalytic efficiency [16,31].

In addition, nitrogen incorporation into the TiO_2 lattice may induce oxygen vacancies and defect states that act as charge trapping sites. These defect sites can prolong the lifetime of photogenerated charge carriers and enhance interfacial redox reactions during photocatalysis [13,26]. Such defect-mediated charge separation is widely recognized as an important factor in improving photocatalytic hydrogen evolution. Furthermore, the nanowire thin-film configuration grown directly on Ti foil may facilitate electron transport between the TiO_2 structure and the conductive substrate, which helps suppress charge recombination and enhances photocatalytic activity [15,24]. Therefore, the superior performance of the NTN-2 photocatalyst can be attributed to a synergistic combination of bandgap narrowing, defect formation, and morphology-induced improvements in charge transport.

To better position the present work within the existing research field, the photocatalytic hydrogen production performance was compared with several TiO_2-based thin-film photocatalysts reported in the literature, as summarized in Table 1. Although experimental conditions such as light source, irradiation time, and reactor configuration vary among studies, the comparison provides a general indication of the performance level of the developed photocatalyst. The N-doped TiO_2 nanowire photocatalyst prepared in this work exhibits a hydrogen evolution rate of 0.795 μmol.cm^{-2}.h^{-1}, which is comparable to or higher than several previously reported TiO_2-based thin-film photocatalysts. The improved performance can be attributed to the synergistic effect of nitrogen doping and the one-dimensional nanowire morphology, which enhances visible-light absorption and facilitates charge transport. Because experimental conditions such as light intensity, sacrificial agents, and reactor configuration vary among studies, the comparison should be considered qualitative.

The photocatalytic process in producing hydrogen (H_2) goes through four stages: the formation of electron-hole pairs (e^-, h^+), the adsorption of water molecules on the surface of the photocatalyst, the reduction and oxidation reactions, and the desorption of products [34]. The overall process can be written in the following equations:

$$\mathrm{TiO_2} \xrightarrow{hv} \mathrm{TiO_2}(e^- + h^+) \quad (5)$$

$$\mathrm{CH_3OH} + \mathrm{H_2O} + h^+ \rightarrow Product\ Oxidation + 2\mathrm{H}^+ + 2e^- \quad (6)$$

$$2\mathrm{H}^+ + 2e^- \rightarrow 2\mathrm{H_2} \quad (7)$$

Using methanol solution to increase the efficiency in producing hydrogen (H_2). Methanol acts as a sacrificial agent, preventing electron-hole recombination and enhancing the efficiency of hydrogen production by providing the additional electrons required in the photocatalytic reaction. The reaction of methanol with a hole (h^+) generates more H^+ ions, which are then reduced into H_2, thereby increasing the efficiency of hydrogen production.

Table 1. Comparison of photocatalytic hydrogen production performance of TiO_2-based thin-film photocatalysts reported in the literature.

Thin film	Morphology	Light source	Time	Hydrogen production rate (μmol/h/cm^2)	Ref.
Ag/TiO_2 NSF	Nano sheets	16 W Hg lamp and 500 W Xenon lamp	3 h	2.7	[32]
CNT-Ce-TiO_2	rough surface morphology	450W Xe-lamp fitted with AM1.5 filter was used to provide one sun condition	5 h	0.214	[33]
N-doped TiO_2	Nanowire	50 W Osram lamp	3 h	0,795	This work

4. Conclusions

N-doped TiO_2 nanowire photocatalysts were successfully synthesized via a hydrothermal method using chitosan as a nitrogen source. XRD analysis confirmed the formation of anatase TiO_2, while SEM observations revealed one-dimensional nanostructures in the form of nanowires and nanorods. Nitrogen incorporation led to improved visible-light absorption and enhanced photocatalytic hydrogen production. Among the synthesized samples, the photocatalyst prepared with 0.8 g of chitosan (NTN-2) exhibited the highest hydrogen evolution rate of 2.385 $\mu mol.cm^{-2}$, corresponding to a hydrogen evolution rate of 0,795 $\mu mol.cm^{-2}.h^{-1}$, indicating that an appropriate dopant concentration plays an important role in optimizing photocatalytic performance. These results demonstrate that the synergistic effect of nitrogen doping and nanostructured morphology can effectively enhance the photocatalytic activity of TiO_2 for solar-driven hydrogen production.

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CRedit Author Statement

Author Contributions: van Attalario: Writing – original draft, Data Curation, Visualization, Investigation, Validation, Methodology. Resha Mutia Rahma: Writing – review & editing, Data Curation, Visualization, Investigation, Formal analysis. Atthar Luqman Ivansyah: Writing – review & editing , Yuly Kusumawati: Writing – review & editing, Validation. Yulia Eka Putri: Writing – review & editing, Visualization, Investigation, Formal analysis, Diana Vanda Wellia: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

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