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Property Enhancement of Electrodeposited p-Cu_2O Thin Films via Hydrothermal Ethanol Etching for Solar Cell Applications Supporting the Sustainable Development Goals (SDGs)

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ABSTRACT

Electrodeposited p-Cu_2O thin films are promising absorber layers for sustainable solar cell applications, but their performance is limited by surface defects, high resistivity, and poor crystallinity. This study investigates hydrothermal ethanol etching as a post-deposition treatment to enhance p-Cu_2O thin films on FTO substrates. The treatment improved crystallinity, refined pyramidal morphology, increased visible-light absorption, reduced surface roughness, and lowered electrical resistivity. These enhancements are attributed to the removal of disordered surface regions and resistive secondary phases. The results indicate that controlled hydrothermal ethanol etching is an effective strategy for improving electrodeposited p-Cu_2O thin films for sustainable photovoltaic applications.

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1. INTRODUCTION

Alternative energy sources have been increasingly adopted to reduce global dependence on fossil fuels and support environmental sustainability. Renewable energy technologies, including hydropower, biomass, geothermal energy, and solar energy, offer cleaner alternatives because they are derived from naturally replenished resources (Al-Janabi and Jumaa, 2026; Solangi and Magazzino, 2025; Trisnoaji *et al.*, 2025). Among these sources, solar energy has attracted considerable attention due to its abundance, accessibility, and potential for large-scale electricity generation through photovoltaic systems (Aldahhan and Akkar, 2026). The development of efficient, low-cost, and environmentally friendly photovoltaic materials is also aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 on affordable and clean energy, SDG 9 on industry, innovation, and infrastructure, and SDG 13 on climate action. Therefore, improving thin-film solar cell materials is an important strategy for advancing sustainable energy technologies and reducing the environmental impact of conventional energy systems.

Thin-film solar cells have gained significant interest because they require less material, offer flexible fabrication routes, and can be produced using relatively simple and cost-effective processes. Various inorganic semiconductor materials have been explored for thin-film and optoelectronic applications, including titanium dioxide, zinc oxide, tin dioxide, tungsten trioxide, molybdenum trioxide, nickel oxide, and cuprous oxide (Arifin *et al.*, 2021; Arifin *et al.*, 2023a; Arifin *et al.*, 2023b; Ávila-López *et al.*, 2025; Kaya *et al.*, 2021; Rezaei *et al.*, 2025). Among these materials, cuprous oxide, or Cu_2O, is considered a promising p-type absorber layer for solar cell applications due to its abundance, low cost, non-toxicity, strong optical absorption, and chemical stability (Fentahun *et al.*, 2021). Copper oxide-based materials have also been widely investigated for optoelectronic applications because their structural and optical properties can be tailored through controlled synthesis conditions (Ali *et al.*, 2024). Cu_2O also possesses suitable optoelectronic properties for photovoltaic devices, including a direct band gap in the visible-light region and favorable carrier characteristics that can support light absorption and charge generation (Farid *et al.*, 2020; Fentahun *et al.*, 2021).

Cu_2O thin films can be fabricated using several techniques, such as thermal oxidation, reactive magnetron sputtering, spray pyrolysis, and electrodeposition (Chen *et al.*, 2021; Winkler *et al.*, 2018; Wisz *et al.*, 2022; Wojcieszak *et al.*, 2022). Among these methods, electrodeposition is particularly attractive because it is simple, inexpensive, scalable, and can be carried out at relatively low temperatures (Ait Hssi *et al.*, 2020; Kim *et al.*, 2022). This method also enables better control over film thickness, morphology, and deposition conditions, making it suitable for the fabrication of Cu_2O thin films on conductive substrates. Moreover, electrodeposition avoids the need for expensive vacuum-based systems, which makes it more practical for the development of low-cost photovoltaic materials (Trinkler *et al.*, 2023).

Despite these advantages, electrodeposited Cu_2O thin films still face several limitations that can affect their photovoltaic performance. Poor crystallinity, surface defects, disordered interfacial layers, and high resistivity may reduce charge transport efficiency and increase recombination losses. These issues can limit the effectiveness of Cu_2O as an absorber layer in thin-film solar cells (Thejasiri *et al.*, 2024). Therefore, post-deposition treatment is required to improve the structural, optical, surface, and electrical properties of Cu_2O thin films. Surface treatment through etching is one possible approach because it can remove unwanted surface layers, reduce defects, refine morphology, and improve electrical contact properties.

Hydrothermal etching treatment is a promising post-deposition process because it combines chemical reaction and elevated temperature in a controlled aqueous or solvent-based environment. This treatment can modify the surface of semiconductor thin films by removing unstable or disordered regions while preserving the main crystalline structure. Previous studies have shown that etching and surface treatment can reduce defect density, improve surface quality, and enhance the electrical properties of thin-film materials (Hirai *et al.*, 2025; Lee *et al.*, 2021; Sun *et al.*, 2023). In Cu_2O-based systems, controlled etching is especially important because excessive etching may damage the film, whereas insufficient etching may not effectively remove surface defects or resistive secondary phases (Niu *et al.*, 2022; Zhu and Panzer, 2016).

In this study, p-Cu_2O thin films were deposited onto fluorine-doped tin oxide (FTO) substrates using the electrodeposition method, followed by hydrothermal ethanol etching treatment. Ethanol was selected as the etching medium to provide a controlled and mild surface modification process. The etching duration was varied to evaluate its influence on the structural, morphological, optical, topological, and electrical properties of the p-Cu_2O thin films. The novelty of this work lies in the use of controlled hydrothermal ethanol etching duration to enhance electrodeposited p-Cu_2O thin films by improving crystallinity, reducing surface roughness, and lowering resistivity. The findings are expected to contribute to the development of low-cost and sustainable Cu_2O-based thin-film solar cells, supporting broader efforts toward clean energy generation and the SDGs.

2. METHODS

The p-Cu_2O thin film was deposited onto an FTO substrate using the electrodeposition method. Prior to deposition, the FTO substrate was cleaned to remove surface contaminants and to improve the adhesion of the deposited film. The Cu_2O electrolyte solution was prepared using 0.4 M copper (II) acetate monohydrate as the base solution, while 3 M lactic acid was added as a complexing agent to stabilize the overall composition of the solution. Potassium hydroxide (KOH) was then added to adjust the pH of the electrochemical solution.

The electrodeposition process was carried out using a 3-electrode setup. The FTO substrate, platinum (Pt), and silver/silver chloride (Ag/AgCl) were used as the working electrode (WE), counter electrode (CE), and reference electrode (RE), respectively. During the deposition of the p-Cu_2O thin film, the bath temperature was maintained at 40 °C, while the pH value was fixed at 12.5. The deposition potential and deposition time were set at -0.40 V versus Ag/AgCl and 2 hours, respectively. After deposition, the p-Cu_2O thin film was dried before undergoing the hydrothermal etching process.

Generally, the electrodeposition of p-Cu_2O thin film involves two main steps. The first step is the reduction of Cu^{2+} ions to Cu^{+} ions, as shown in reaction (R1). The second step is the precipitation of Cu^{+} ions to form Cu_2O due to the solubility limitation of Cu^{+} ions, as shown in reaction (R2). The potential region associated with Cu_2O deposition generally occurs at less negative values compared to the potential range required for metallic copper formation. In addition, current transients provide useful information on the nucleation and growth behavior of the deposited Cu_2O film, which helps to explain its deposition mechanism (see reactions (R1) and (R2))

$$Cu^{2+} + e^{+} \rightarrow Cu^{+} \quad \text{(R1)}$$

$$2Cu^{+} + H_2O \rightarrow Cu_2O + 2H^{+} \quad \text{(R2)}$$

Consequently, hydrothermal ethanol etching treatment was carried out to improve the surface quality of the p-Cu_2O thin film. This process follows a similar principle to the hydrothermal method, where chemical reaction and elevated temperature are applied in a closed system. Diluted ethanol was selected as the etching medium. The hydrothermal temperature was fixed at 150 °C, while the ethanol concentration was maintained at 0.15 mol. The etching duration was varied at 1, 3, and 5 hours to investigate the effect of treatment time on the properties of the p-Cu_2O thin film.

During the etching process, the deposited p-Cu_2O thin film was placed vertically inside a cleaned Teflon chamber. Diluted ethanol was then added into the inner Teflon chamber until the deposited p-Cu_2O thin film was fully immersed. The autoclave was tightly sealed to prevent leakage during the heating process. The hydrothermal etching treatment was then conducted at the fixed temperature and selected etching durations in a closed oven. The illustration of the hydrothermal etching treatment for the p-Cu_2O thin film is presented in **Figure 1**.

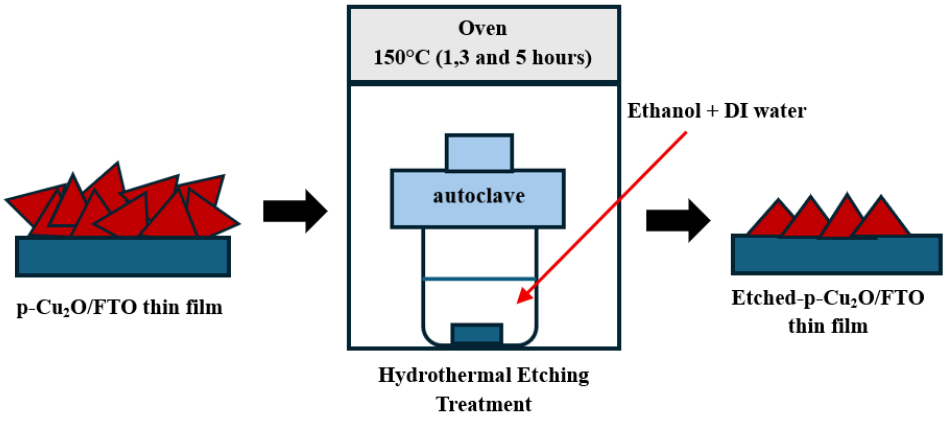

Figure 1. Illustration of hydrothermal etching treatment for p-Cu_2O thin film

Several characterization techniques were employed to evaluate the properties of the etched p-Cu_2O thin films. Structural characterization was performed using X-ray diffraction (XRD) with Cu Kα radiation at a wavelength of 1.54 Å over a 2θ range of 20 to 80° to determine the crystal structure and preferred orientation of the films. The morphological properties were characterized using field emission scanning electron microscopy (FE-SEM) at an accelerating voltage of 15,000 V and a magnification of 50,000×. Meanwhile, ultraviolet-visible spectroscopy (UV-Vis) was used to analyze the optical transmittance spectrum in the wavelength range of 300 to 800 nm. Finally, the topological and electrical properties of the thin films were characterized using atomic force microscopy (AFM) and a four-point probe system, respectively.

3. RESULTS AND DISCUSSION

Here, we discussed the influence of hydrothermal ethanol etching on the structural, morphological, optical, topological, and electrical properties of electrodeposited p-Cu_2O thin films. The as-deposited film was used as a reference, while the etched samples were treated for 1, 3, and 5 hours to evaluate the effect of etching duration. The discussion is aligned with the main focus of this study, which is the property enhancement of electrodeposited p-Cu_2O thin films via hydrothermal ethanol etching toward sustainable solar cell applications. In

addition to the material improvement, the contribution of this work to the SDGs is also discussed, particularly in relation to clean energy, sustainable innovation, and climate action.

3.1. Relevance to SDGs

The enhancement of electrodeposited p-Cu_2O thin films is relevant to the development of sustainable photovoltaic materials. Cu_2O is considered a promising absorber layer because it is abundant, low cost, non-toxic, chemically stable, and suitable for visible-light absorption. These characteristics make Cu_2O attractive for thin-film solar cell applications, especially in the development of affordable and environmentally friendly energy technologies. Therefore, improving the quality of Cu_2O thin films supports SDGs. Similar links between engineering research, material development, and SDG-oriented innovation have also been discussed in previous studies (Nandiyanto *et al.*, 2025; Nandiyanto *et al.*, 2024; Fiandini *et al.*, 2024). Detailed information regarding SDGs is reported elsewhere (Ragadhita *et al.*, 2026).

For this study, it relates to SDG 7, which focuses on affordable and clean energy. The fabrication strategy used in this study also supports SDG 9 on industry, innovation, and infrastructure. Electrodeposition is a simple, low-temperature, and scalable deposition method that does not require expensive vacuum-based equipment. Meanwhile, hydrothermal ethanol etching provides a controlled post-deposition treatment to refine the film surface and improve its functional properties. The combination of electrodeposition and ethanol etching offers a practical pathway for developing thin-film absorber materials using relatively simple processing conditions. In addition, this research supports SDG 13 on climate action. The improvement of Cu_2O thin films for solar cell applications may contribute to the broader adoption of renewable energy technologies, which are essential for reducing dependence on fossil fuels and mitigating greenhouse gas emissions. Thus, the property enhancement achieved in this study is not only important for material performance but also contributes to the development of sustainable solar energy technologies.

3.2. Structural Properties

The structural properties of the as-deposited and etched p-Cu_2O thin films were analyzed using X-ray diffraction (**Figure 2**). Patterns (a), (b), (c), and (d) show the XRD patterns of the as-deposited p-Cu_2O thin film and the films etched using ethanol for 1, 3, and 5 hours, respectively. The diffraction peaks observed at 36.42, 42.31, 61.38, and 73.52° correspond to the (111), (200), (220), and (311) crystal planes of p-Cu_2O, respectively. Among these peaks, the highest intensity appeared at 36.42°, which corresponds to the preferred (111) orientation. This confirms the successful formation of crystalline p-Cu_2O on the FTO substrate. The result is consistent with literature (Mohamad *et al.*, 2020), who reported that the Cu_2O semiconductor phase commonly shows a strong diffraction peak near 36.4° corresponding to the (111) plane.

After hydrothermal ethanol etching, the main diffraction peaks remained at similar positions, indicating that the etching treatment did not change the primary Cu_2O crystal phase. However, the peak intensity increased after etching, especially for the sample etched for 5 hours. This suggests that the etching treatment improved the crystalline quality of the p-Cu_2O thin film. The improvement can be attributed to the removal of weakly crystallized regions, disordered surface layers, and possible contaminants from the film surface. Etching is commonly associated with the preferential removal of unstable surface regions, allowing more ordered crystalline domains to become dominant. In general, etching treatment can

modify surface characteristics by removing less stable surface regions and improving surface activity, as demonstrated in other etched catalytic and functional material systems (Rao *et al.*, 2024).

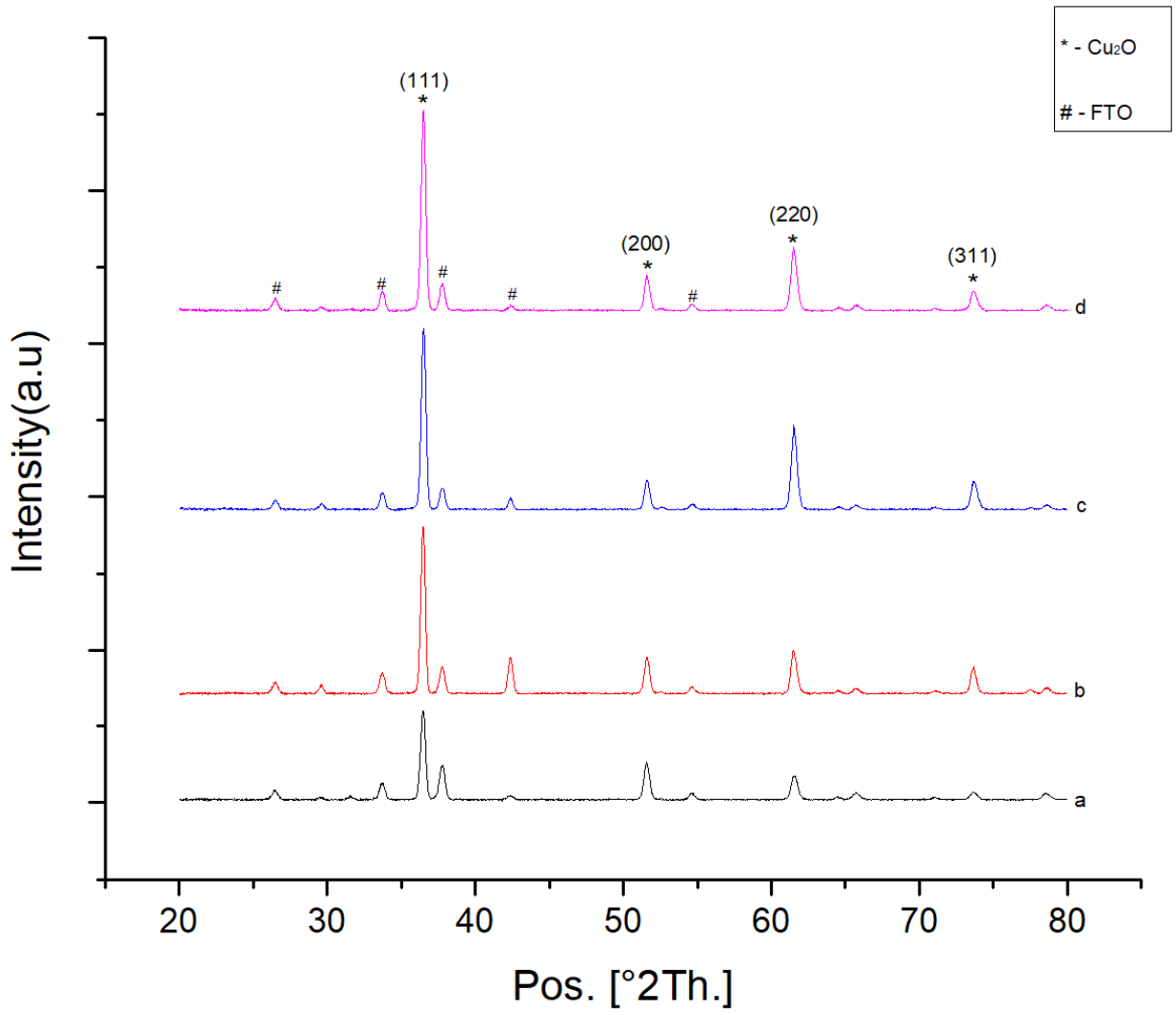

Figure 2. XRD pattern of p-Cu_2O thin film: (a) as-deposited and etched by ethanol for (b) 1, (c) 3, and (d) 5 hours, respectively.

The enhancement of crystallinity is important because crystal quality strongly influences charge transport in semiconductor thin films. Disordered regions, surface traps, and defects may increase charge recombination and limit carrier mobility. By reducing these defective regions, hydrothermal ethanol etching may support better charge transfer in the p-Cu_2O thin film. This is relevant for solar cell absorber layers, where efficient charge separation and transport are required to improve device performance. Trap-assisted recombination can significantly affect charge generation and recombination behavior in optoelectronic materials (Ma *et al.*, 2023). Therefore, the stronger diffraction intensity after etching indicates that controlled hydrothermal ethanol etching can enhance the structural quality of electrodeposited p-Cu_2O thin films.

The crystallite size of the p-Cu_2O thin films was calculated using Scherrer's Equation, as shown in Equation (1). In this equation, λ represents the X-ray wavelength, θ is the Bragg

diffraction angle, and d is the full width at half maximum of the corresponding diffraction peak. Equation (1) was used to evaluate the relationship between FWHM and crystallite size.

$$D = \frac{0.94\lambda}{\beta \cos\theta} \quad (1)$$

The FWHM and crystallite size values are summarized in Table 1. The as-deposited p-Cu_2O thin film exhibited an FWHM value of 0.2558° and a crystallite size of 5.23 nm. After etching, the FWHM values changed to 0.3346, 0.3149, and 0.3936° for the samples etched for 1, 3, and 5 hours, respectively. The corresponding crystallite sizes were 7.1, 6.4, and 6.7 nm. These results indicate that the etching duration influenced the microstructural characteristics of the p-Cu_2O thin films.

Table 1. Structural properties of the p-Cu_2O reflection peak

SAMPLE	FWHM (°)	CRYSTALLITE (nm)
As-deposited	0.2558	5.23
1 hr	0.3346	7.10
3 hrs	0.3149	6.4
5 hrs	0.3936	6.7

The 5-hour etched sample showed the highest FWHM value and maintained strong Cu_2O diffraction intensity. This suggests that longer etching duration promoted more effective surface modification and removal of unstable layers. However, etching must be carefully controlled because excessive etching may damage the film surface or dissolve the active Cu_2O layer. Therefore, the 5-hour treatment was considered the optimum condition in this study because it improved the structural characteristics while maintaining the integrity of the thin film. This finding is in agreement with literature (Ahmad Ramli *et al.*, 2022), who reported that etching treatment can enhance thin-film properties within a controlled treatment window. Similarly, etching can be beneficial for surface modification when the process is properly controlled (Hrbek *et al.*, 2020).

3.3. Morphological Properties

The morphology and cross-sectional structure of the p-Cu_2O thin films were examined using field emission scanning electron microscopy. **Figures 3(a) and 3(b)** show the surface morphology and cross-sectional image of the as-deposited p-Cu_2O thin film, respectively. As shown in **Figure 3(a)**, the as-deposited film consisted of compact pyramidal grains distributed across the FTO substrate. The pyramidal cubic structure confirms the typical morphology of Cu_2O and supports the XRD result, where the (111) plane was identified as the dominant orientation. This relationship shows that the structural and morphological properties are closely related. Cu_2O thin films prepared using electrodeposition commonly exhibit strong orientation behavior depending on deposition conditions and complexing agents (Arulkumar *et al.*, 2023).

The cross-sectional image in **Figure 3(b)** confirms the formation of a continuous p-Cu_2O layer on the FTO substrate with a film thickness of 2.25 µm. The film showed good coverage, and no obvious holes or gaps were observed between the pyramidal grains. This compact morphology is important for absorber layers because a continuous surface can improve light absorption and reduce leakage pathways in solar cell structures.

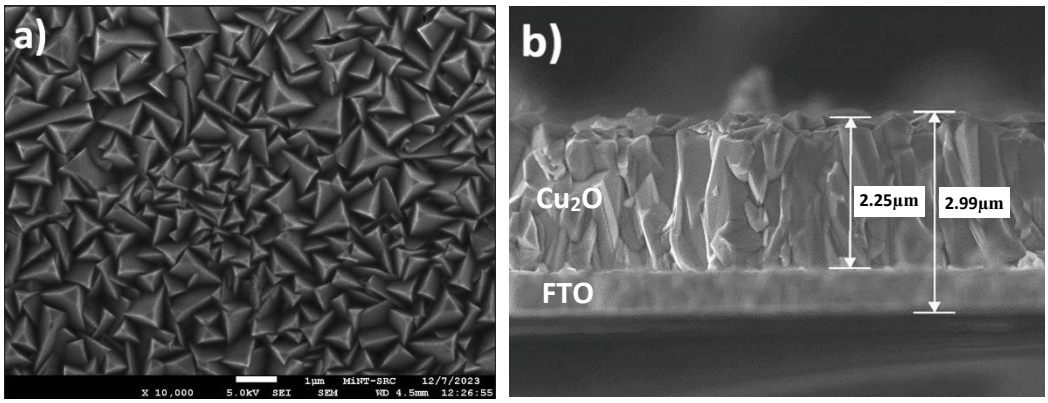

Figure 3. FE-SEM images of (a) surface morphology and (b) cross-section of as-deposited p-Cu_2O thin film.

After hydrothermal ethanol etching, the morphology of the p-Cu_2O thin films changed gradually with increasing etching duration. **Figures 4(a) and 4(b)** show the surface morphology and cross-sectional image of the sample etched for 1 hour, respectively. As shown in **Figure 4(a)**, the pyramidal structure was still maintained after etching, but slight surface refinement began to appear. **Figure 4(b)** shows that the film thickness decreased from 2.25 to 2.18 µm after 1 hour of etching, indicating that ethanol etching removed a small portion of the surface layer.

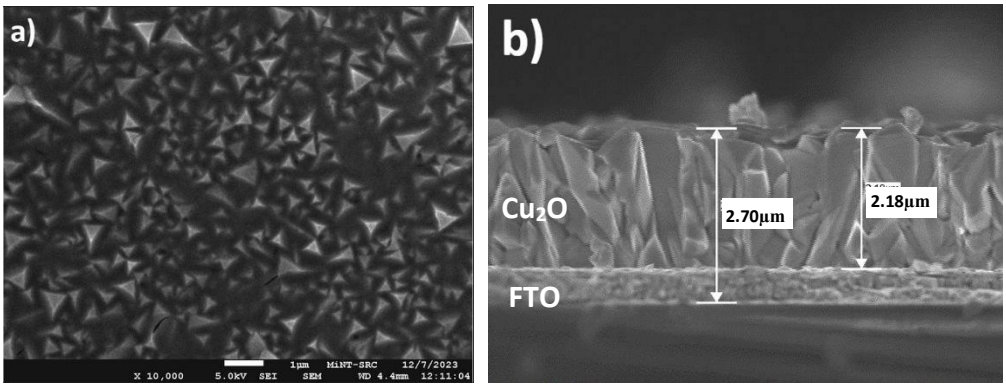

Figure 4. FE-SEM images of (a) surface morphology and (b) cross-section of etched p-Cu_2O thin film for 1 hour.

Figures 5(a) and 5(b) present the surface morphology and cross-sectional image of the p-Cu_2O thin film etched for 3 hours, respectively. The surface morphology in **Figure 5(a)** shows that the pyramidal grains became more defined compared with the 1-hour etched sample. Meanwhile, **Figure 5(b)** shows that the film thickness further decreased to 2.16 µm. This confirms that longer etching duration increased the removal of the surface layer while still preserving the main Cu_2O structure.

Figures 6(a) and 6(b) show the surface morphology and cross-sectional image of the p-Cu_2O thin film etched for 5 hours, respectively. As shown in **Figure 6(a)**, the pyramidal grains appeared more refined and well-defined after prolonged etching. The sharpening of the grain facets indicates that hydrothermal ethanol etching selectively removed disordered surface regions and exposed more stable crystalline planes. **Figure 6(b)** shows that the film thickness decreased to 1.97 µm after 5 hours of etching. The gradual reduction in thickness from the as-deposited sample to the 5-hour etched sample confirms that the etching process continuously removed part of the Cu_2O surface layer as treatment time increased.

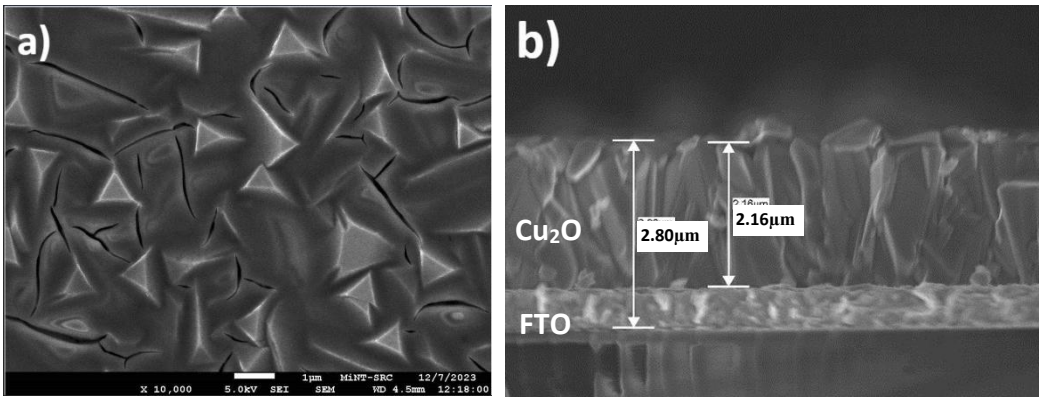

Figure 5. FE-SEM images of (a) surface morphology and (b) cross-section of etched p-Cu_2O thin film for 3 hours.

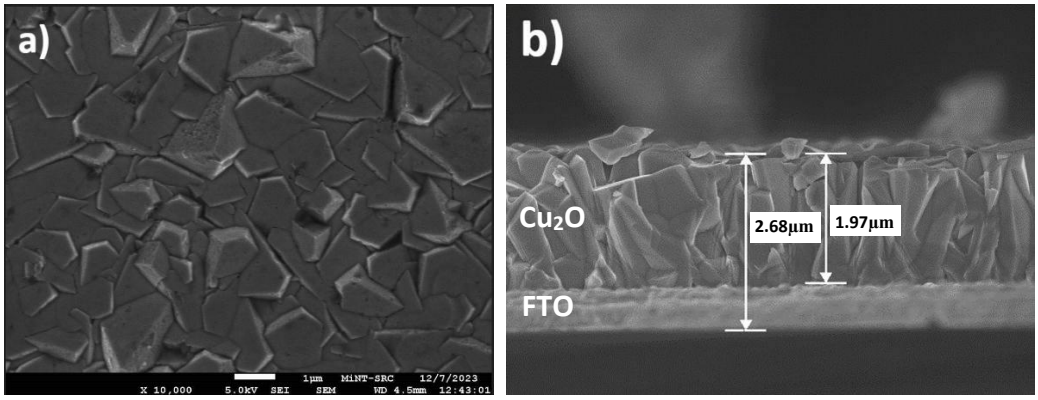

Figure 6. FE-SEM images of (a) surface morphology and (b) cross-section of etched p-Cu_2O thin film for 5 hours.

The thickness reduction observed in **Figures 3(b), 4(b), 5(b), and 6(b)** demonstrates the direct influence of etching duration on the physical structure of the p-Cu_2O thin film. This result is consistent with reference (Zulkifli *et al.*, 2024), who reported that thin-film thickness can decrease with increasing hydrothermal reaction or etching time. In this study, the 5-hour etched sample showed the most favorable morphology because it maintained the Cu_2O layer while producing clearer pyramidal facets. However, further extension of the etching process may lead to excessive thinning, surface degradation, or delamination. Therefore, 5 hours was identified as the optimum etching duration for morphological improvement without destroying the active p-Cu_2O layer.

3.4. Optical Properties

The optical properties of the as-deposited and etched p-Cu_2O thin films were analyzed using ultraviolet-visible spectroscopy. **Figures 7(a), 7(b), 7(c), and 7(d)** show the absorbance spectra of the as-deposited p-Cu_2O thin film and the samples etched using ethanol for 1, 3, and 5 hours, respectively. The absorbance spectra show that all samples exhibited an absorption edge in the visible-light region. For the as-deposited sample, the absorption edge was observed around 650 nm, indicating that the electrodeposited p-Cu_2O thin film was able to absorb visible light. This optical response is important because the absorber layer in a solar cell must effectively harvest photons in the visible region to generate charge carriers.

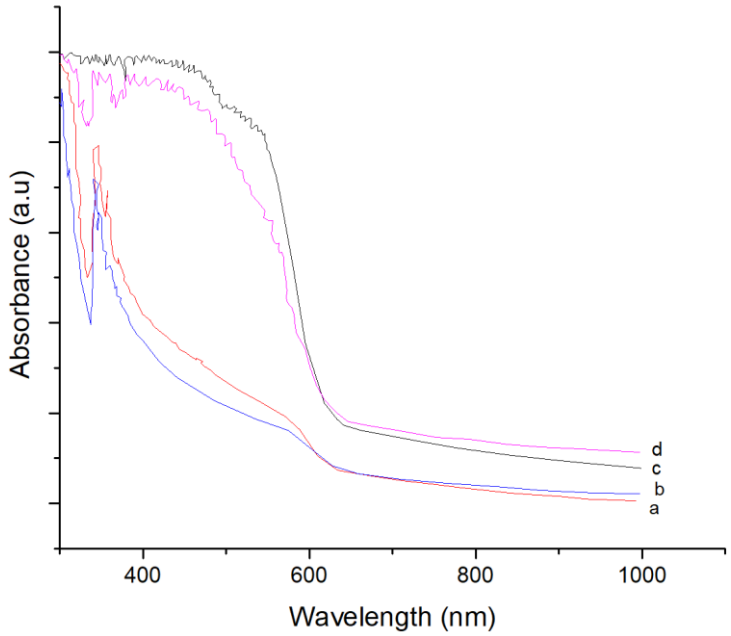

Figure 7. Absorbance spectrum of p-Cu_2O thin film: (a) as-deposited and etched by ethanol for (b) 1, (c) 3 hours, and (d) 5 hours.

After hydrothermal ethanol etching, the absorbance behavior improved, especially for the samples etched for 3 and 5 hours. The stronger absorption edge observed in **Figures 7(c) and 7(d)** suggests that longer etching duration enhanced the optical response of the p-Cu_2O thin films. This improvement may be attributed to the refined morphology and improved crystallinity, as discussed in the structural and morphological analyses. Better crystallinity can reduce localized defects and improve optical transition behavior, while a more defined surface morphology can influence light interaction with the film surface.

The optical band gap was estimated using the Tauc's equation, as shown in Equation (2). In this equation, α represents the absorption coefficient, h is Planck's constant, v is the frequency, and Eg is the optical band gap. The band gap was determined by extrapolating the linear region of the plot of $(\alpha hv)^2$ against photon energy.

$$(ahv)^2 = \mathrm{A}(hv - \mathrm{Eg}) \tag{2}$$

Figure 8 shows the extrapolated energy band gap of the p-Cu_2O thin film etched for 5 hours. The estimated band gap was 1.7 eV, which lies within the reported range for Cu_2O-based materials. This value indicates that the etched p-Cu_2O thin film is suitable for visible-light absorption and has potential for solar cell absorber applications. CuO and Cu_2O materials exhibit optical properties that are strongly influenced by structure, phase formation, and synthesis conditions (Kumar *et al.*, 2019). The optical behavior of copper oxide-based materials can be adjusted through controlled material composition and structural modification (Bayat and Sheibani, 2022). Therefore, the band gap obtained in this study supports the role of hydrothermal ethanol etching in improving the optical suitability of p-Cu_2O thin films for photovoltaic applications.

The optical improvement observed after etching is also consistent with the XRD and FE-SEM findings. The 5-hour etched sample showed stronger Cu_2O diffraction intensity, clearer pyramidal morphology, and reduced film thickness. These changes suggest that the etching process removed defective surface regions that may otherwise interfere with optical

absorption. As a result, hydrothermal ethanol etching contributed to better visible-light absorption while maintaining the functional Cu_2O phase.

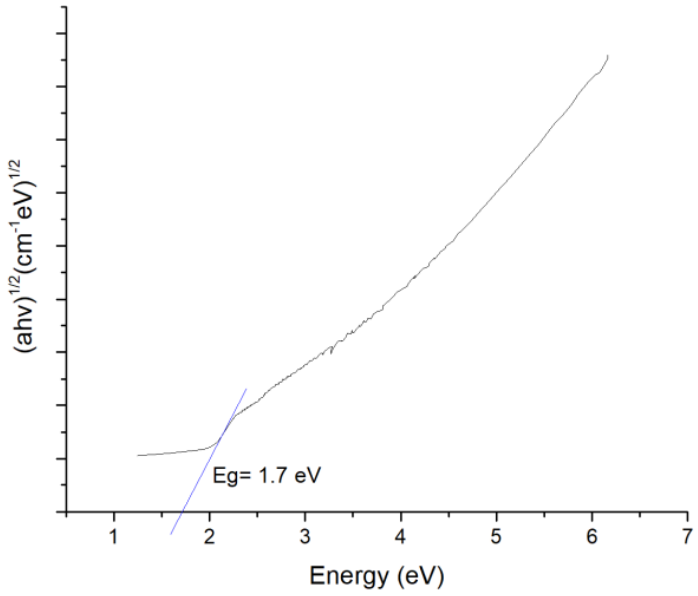

Figure 8. Extrapolated energy bandgap of etched p-Cu_2O thin film for 5 hours.

3.5. Surface Topography and Roughness

The surface topology and root mean square roughness of the p-Cu_2O thin films were analyzed using atomic force microscopy. **Figures 9(a), 9(b), 9(c), and 9(d)** show the AFM images of the as-deposited sample and the samples etched using ethanol for 1, 3, and 5 hours, respectively. As shown in **Figure 9(a)**, the as-deposited p-Cu_2O thin film exhibited a pyramidal surface structure with visible grain edges. This result agrees with the FE-SEM image in **Figure 3(a)**, where compact pyramidal grains were observed on the film surface.

After etching, the surface topology changed progressively with increasing treatment duration. **Figure 9(b)** shows that the sample etched for 1 hour still maintained the pyramidal structure, but the surface became slightly smoother than the as-deposited film. **Figure 9(c)** shows further surface modification after 3 hours of etching, where the edges of the pyramidal grains became more refined. **Figure 9(d)** shows that the 5-hour etched sample exhibited the lowest surface roughness among the samples. This indicates that hydrothermal ethanol etching was effective in reducing surface irregularities.

The roughness values obtained from AFM analysis are summarized in **Table 2**. The as-deposited p-Cu_2O thin film showed an Rq value of 79.798 nm. After etching for 1, 3, and 5 hours, the Rq values decreased to 63.654, 60.784, and 53.067 nm, respectively. The continuous decrease in surface roughness indicates that longer etching duration promoted surface smoothing. This behavior can be explained by the preferential dissolution of high-energy surface sites, such as protrusions, weakly bonded atoms, and disordered grain boundary regions. Surface roughness can strongly influence dielectric and thin-film properties, particularly because rough surfaces may increase local defects and non-uniform electrical behavior (Song *et al.*, 2022).

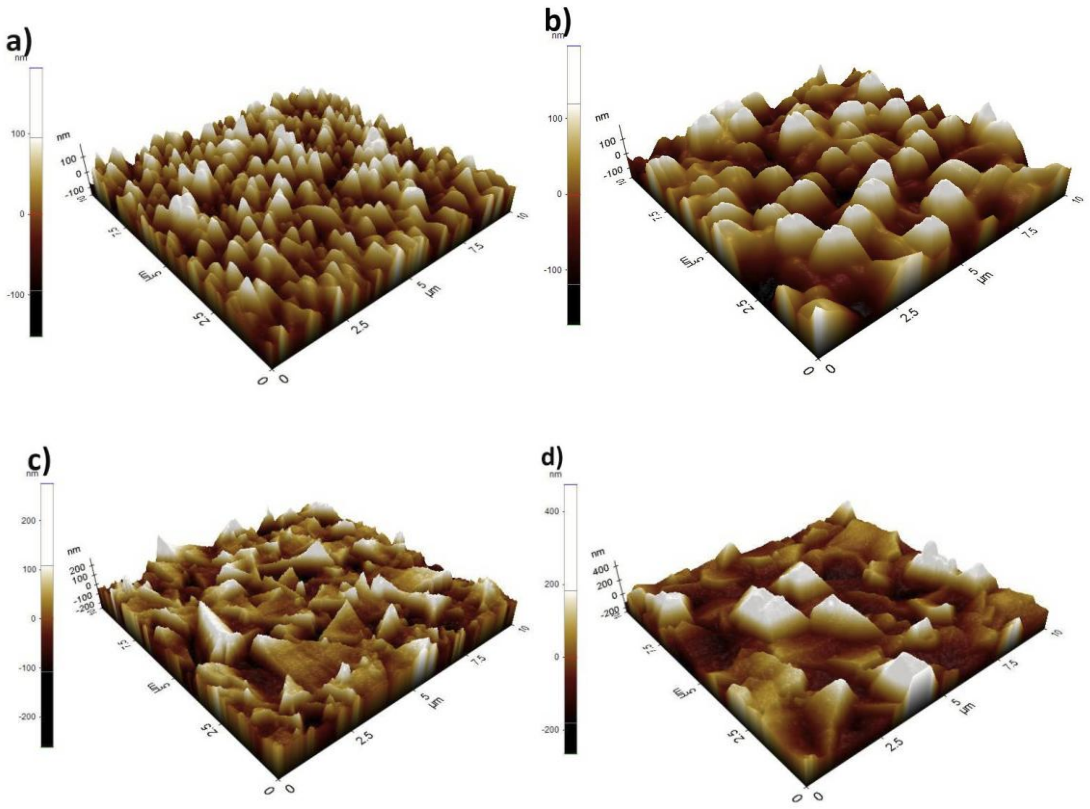

Figure 9. AFM images of the p-Cu_2O thin film on (a) as-deposited sample and etched by ethanol for (b) 1, (c) 3, and (d) 5 hours, respectively.

Table 2. RMS roughness of the sample.

SAMPLE	*Rq* (nm)
As-deposited	79.798
Etched 1 hr	63.654
Etched 3 hrs	60.784
Etched 5 hrs	53.067

The decrease in roughness is important for solar cell applications because a smoother and more uniform absorber surface can improve contact formation with adjacent layers. It may also reduce interfacial recombination and improve charge transport across the device structure. In this study, the 5-hour etched p-Cu_2O thin film showed the lowest roughness, suggesting that this condition produced the most favorable surface topology. This result supports the structural and morphological findings, where 5-hour etching resulted in improved crystallinity and well-defined pyramidal grains.

3.6. Electrical Properties

The electrical properties of the p-Cu_2O thin films were evaluated using a four-point probe measurement system. **Figure 10** shows the relationship between resistivity and etching duration. The as-deposited p-Cu_2O thin film showed a resistivity value of 0.081 Ω/m. After hydrothermal ethanol etching for 1 hour, the resistivity decreased to 0.055 Ω/m. Further reduction was observed for the samples etched for 3 and 5 hours, with resistivity values of 0.032 and 0.019 Ω/m, respectively.

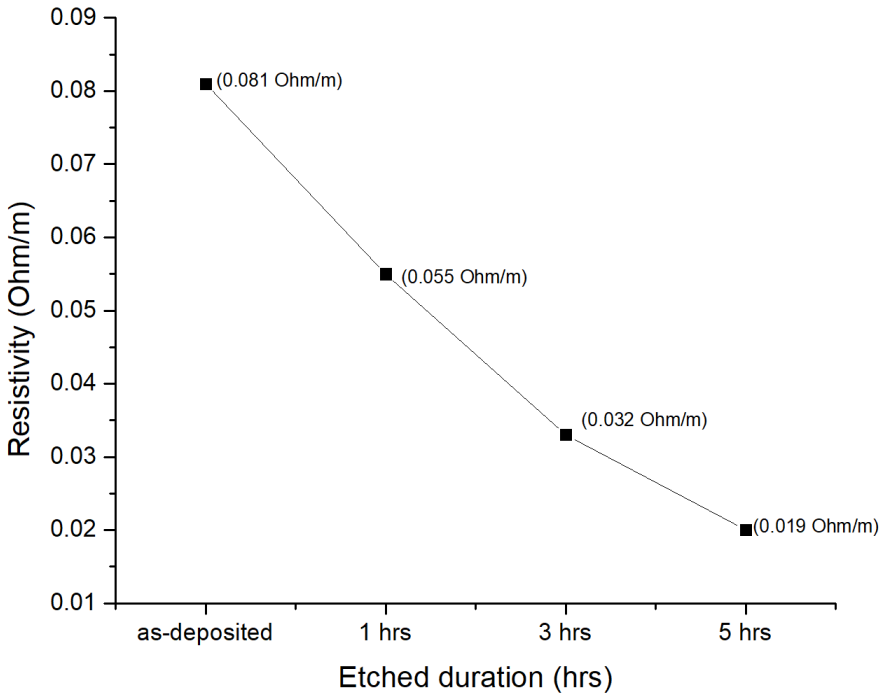

Figure 10. Resistivity against etched duration.

The continuous decrease in resistivity indicates that hydrothermal ethanol etching improved the electrical transport properties of the p-Cu_2O thin films. This improvement can be attributed to the removal of resistive surface layers, reduced defect density, and improved grain boundary characteristics. A rough or defective surface may increase charge trapping and carrier scattering, which can increase electrical resistance. After etching, the reduction in surface roughness and the improvement in crystallinity likely contributed to better carrier transport. Etching can modify surface properties and influence electrical behavior in oxide thin films (Lee *et al.*, 2021). Similarly, copper oxide thin films may contain secondary copper oxide phases, such as CuO and Cu_2O, which can influence their surface morphology, phase evolution, and electrical properties (Rajak *et al.*, 2025).

The lowest resistivity was obtained from the 5-hour etched sample, indicating that this treatment condition provided the most effective surface modification. The reduced resistivity is beneficial for solar cell absorber layers because it can support improved charge collection and lower series resistance in device structures. When combined with the enhanced crystallinity, refined morphology, stronger visible-light absorption, and lower surface roughness, the electrical result confirms that 5-hour hydrothermal ethanol etching is the optimum condition in this study.

The results demonstrate that hydrothermal ethanol etching effectively enhanced the properties of electrodeposited p-Cu_2O thin films. The 5-hour etched sample showed the best combination of structural, morphological, optical, topological, and electrical characteristics. These improvements are directly aligned with the objective of developing enhanced Cu_2O thin films for sustainable solar cell applications. The findings suggest that controlled ethanol etching can serve as a practical post-deposition treatment for improving low-cost absorber materials and supporting the development of sustainable photovoltaic technologies.

4. CONCLUSION

Electrodeposited p-Cu_2O thin films were successfully enhanced through hydrothermal ethanol etching treatment. The 5-hour etched sample exhibited the most improved overall properties, including stronger Cu_2O crystallinity with a dominant (111) orientation, refined pyramidal morphology, improved visible-light absorption, lower surface roughness, and reduced electrical resistivity. These improvements indicate that controlled ethanol etching effectively removes disordered surface regions and improves the functional quality of p-Cu_2O thin films. Therefore, hydrothermal ethanol etching can be considered an effective post-deposition strategy for improving electrodeposited p-Cu_2O thin films toward sustainable solar cell applications. The findings also support the broader direction of the SDGs, particularly clean energy development, sustainable innovation, and climate action.

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5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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