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Review

Optimizing Copper-Aluminum Photovoltaic Cells with Sodium Chloride Gel Electrolyte under Neon Lamp Ilumination: A Comprehensive Review

Dhea Nurfadilla Chandra[1*], Mohammad Abdullah[2], Adhan Efendi[3], Ilham Saputra[4]

[1]Department of Chemistry, Faculty of Mathematics and Natural Science, Universitas Negeri Padang, Padang, Indonesia
[2]Chemical Engineering Studies, College of Engineering, Universiti Teknologi MARA Johor Branch, Johor Bahru, Johor, Malaysia
[3]Graduate Institute of Precision Manufacturing, National Chin-Yi University of Technology, Taichung, Taiwan
[4]Department of Mechanical Engineering, College of Engineering, National Yunlin University of Science and Technology, Douliou, Taiwan

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Abstract. Photovoltaic cells are devices capable of converting light energy into electrical energy through the photovoltaic effect, where absorbed photons in semiconductor materials generate an electric current. Ideally, photovoltaic cells should offer high efficiency, long-term stability, and low production costs under various lighting conditions. In reality, most conventional photovoltaic technologies, such as crystalline silicon, still suffer from high production costs and performance degradation, especially under long-term exposure and high humidity. As an alternative, copper-aluminum (Cu-Al) based photovoltaic cells with sodium chloride (NaCl) gel electrolyte have been developed, providing reasonable energy conversion efficiency, low material costs, and simple fabrication. The NaCl gel enhances ionic conductivity and system stability, while calcination of Cu into CuO improves the semiconductor properties of the active layer. The urgency of this research lies in the need for renewable energy systems that are affordable, easy to produce, and durable, particularly for remote areas or off-grid applications. Therefore, this article aims to provide a comprehensive review of the optimization of Cu-Al photovoltaic cells with NaCl gel electrolyte under neon lamp illumination, highlighting technical challenges, performance enhancement mechanisms, and future development prospects. This article includes references from publications between 2019 and 2025.

Corresponding Author :
Dhea Nurfadilla Chandra
Department of Chemistry, Faculty of Mathematics and Natural Science,
Universitas Negeri Padang, Padang, Indonesia
Email : dheanurfadillachandra22@gmail.com

1. Introduction

Solar energy is one of the most abundant renewable energy sources on Earth, derived from sunlight and utilized for various applications, including electricity generation. The increasing global energy demand and concerns over the environmental impacts of fossil fuels have emphasized the importance of solar energy as a sustainable and clean alternative. Among the most established technologies for converting solar energy into electricity are solar cells or photovoltaic (PV) cells, which operate based on the photovoltaic effect a phenomenon in which certain semiconductor materials generate electric current upon light exposure [1].

The development of photovoltaic cell technology has progressed rapidly, evolving from first-generation crystalline silicon-based devices to newer generations that incorporate organic materials, perovskite structures, and gel-based electrolytes to improve device efficiency and stability. Research has also focused on employing low-cost, abundant electrode materials such as copper (Cu) and aluminum (Al) to reduce production costs without compromising overall performance [2].

Both Cu and Al possess specific advantages that make them attractive for photovoltaic applications. Copper (Cu) is known for its high electrical conductivity, ease of fabrication, and relatively low cost compared to noble metals [3]. Aluminum (Al), on the other hand, offers excellent material abundance, lightweight properties, and reflective characteristics that can enhance light absorption in certain cell designs [4]. However, both materials present limitations. Cu is prone to oxidation and corrosion, particularly in aggressive electrolyte environments, which can reduce the device's operational lifespan [5]. Meanwhile, Al, though lightweight and affordable, tends to form an oxide layer that may interfere with electrical contact and electrode interface stability [6].

In addition to electrode material challenges, the stability of the electrolyte system is a crucial factor for the long-term performance of photovoltaic cells. Gel-based electrolytes formulated with sodium chloride (NaCl) provide benefits such as mechanical flexibility, improved thermal stability, and ease of processing [7]. Nonetheless, the stability of NaCl gel electrolytes is influenced by several critical factors, including NaCl ion concentration, gel thickness, material dispersion homogeneity, and resistance to temperature fluctuations or repeated light exposure. Moreover, structural degradation of the gel due to drying, contamination, or chemical reactions with the electrodes can significantly compromise overall system efficiency [8].

Most previous studies have explored Cu-Al electrodes in conjunction with liquid or solid-state electrolytes, leaving the true potential of gel-based systems underexplored [9]. Additionally, recurring degradation of Cu-Al electrodes due to oxidation remains a significant concern requiring further investigation [10]. Therefore, this comprehensive review aims to analyze the opportunities, challenges, and innovations offered by implementing Cu-Al electrodes with NaCl gel electrolytes in photovoltaic cells under neon lamp illumination, addressing key gaps in existing research.

2. Experimental Section

This study employs a systematic review method to analyze various research findings related to the optimization of copper-aluminum (Cu-Al) based photovoltaic cell performance using sodium chloride (NaCl) gel electrolyte under neon lamp illumination. The initial stage involves determining the focus of the review, specifically on efficiency, stability, and the role of NaCl in the Cu-Al photovoltaic system. Subsequently, research questions are formulated, and inclusion criteria are established, such as selecting articles published within the last five years, relevant to the topic, and peer-reviewed.

The next stage is conducting an article search using scientific databases such as Scopus, Google Scholar, and ScienceDirect with relevant keyword combinations. The retrieved articles are screened based on the predetermined criteria, followed by quality evaluation using instruments such as methodological validity checklists and relevance assessments. Important data such as electrolyte composition, optimization parameters, the electrodes used and efficiency results were collected. Finally, a comparative analysis between studies is performed to draw conclusions regarding the best optimization strategies for Cu-Al photovoltaic systems with NaCl gel electrolyte under neon lamp illumination.

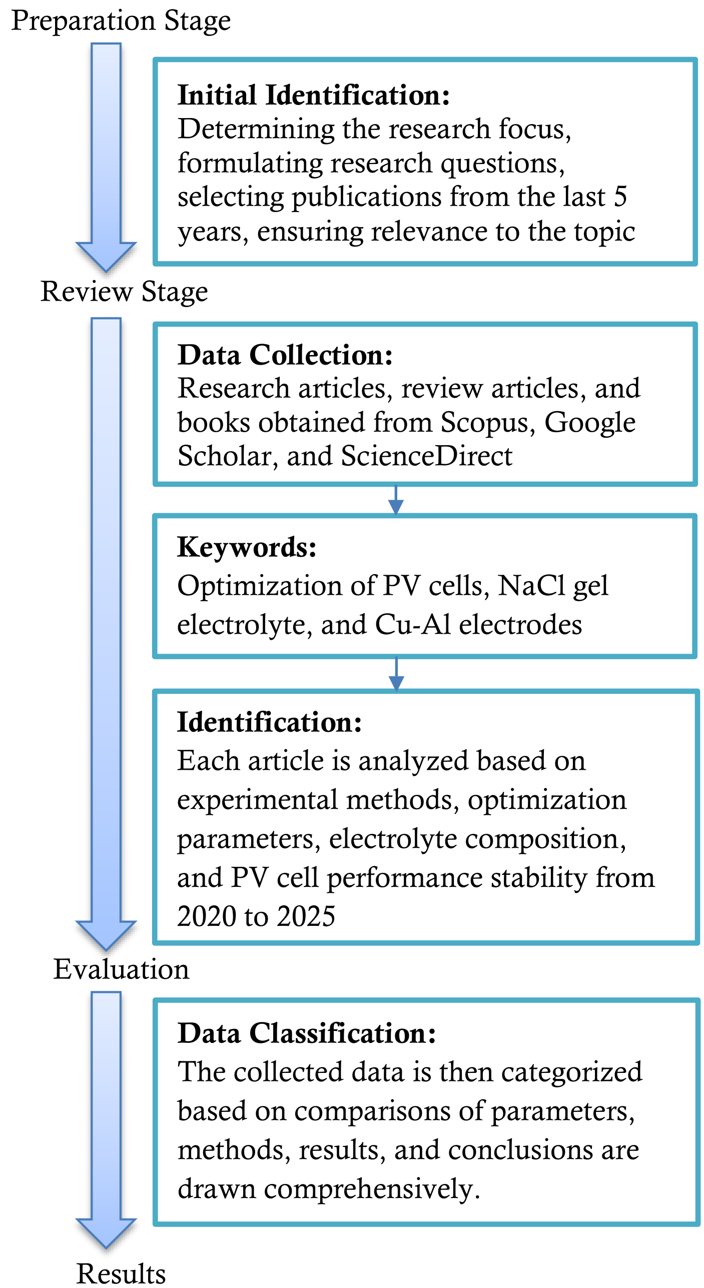

Figure 1. Literature review research flow

Table 1. Comparative studies literature review

No	Title	Year	Result
1	Inverted Perovskite Photovoltaics Using Flame Spray Pyrolysis Solution Based $CuAlO_2$/CuO Hole-Selective Contact [11]	2019	The use of $CuAlO_2$ film as a hole-selective layer in perovskite solar cells, efficiency increased and hysteresis effect reduced; evidence that the combination of Cu–Al oxide can enhance the performance of photovoltaic cells.
2	Efficiency of Aluminium and Copper Coated Aluminium Electrode in Hydrogen Fuel Generation from Rain Water [12]	2020	Cu-coated Al electrodes were used for rainwater electrolysis, with NaCl as the electrolyte, The combination of a Cu-Al anode and an Al cathode achieved hydrogen efficiency of up to 11% at room temperature, increasing to 29% at 60 °C.
3	Cathodic Protection Using Aluminum in Chloride Molten Salts for Thermal Energy Storage [13]	2020	Cathodic protection of aluminum in molten chloride salts, relevant for solar-thermal systems, demonstration that aluminum remains stable in NaCl–KCl molten solution at high temperatures, which is crucial for high-temperature cell applications.
4	Electronic Structures and Photovoltaic Properties of Copper-, Sodium- and Ethylammonium-Added $CH_3NH_3PbI_3$ Perovskite Compound † [14]	2023	The addition of copper (Cu), sodium (Na), and ethylammonium (EA) to $CH_3NH_3PbI_3$ perovskite improves structural stability, enhances light absorption by reducing the bandgap, and increases solar cell efficiency up to 19.1%.
5	Copper–Oxide (Cu_2O) Sheet Based Solar Cell [15]	2024	Cu_2O sheets were fabricated by copper oxidation and tested with NaCl saline electrolyte, the NaCl solution as an electrolyte enhanced output performance compared to plain water; both light intensity and NaCl concentration significantly influenced the results.
6	Sustainable Recovery of Silver and Copper Photovoltaic Metals from Waste Silver Pastes [16]	2024	Extraction of Cu and Ag from conductive paste waste using thiosulfate combined with UV irradiation, metal recovery rates reached up to 90%, relevant for recycling Cu components in photovoltaic cells – although not a direct Cu–Al system, the results indicate the potential for high electrolytic efficiency.
7	Molten sodium copper chloride batteries: electrolyte and interface advances [17]	2024	A stable electrolyte was identified for intermediate temperatures, along with the degradation mechanisms showing potential applicability to Cu–Al gel systems.
8	The Enhancement Discharge Performance by Zinc-Coated Aluminum Anode for Aluminum–Air Battery in Sodium Chloride Solution [18]	2024	Zinc coating on aluminum anodes in 3.5% NaCl solution significantly improved the performance of Aluminum–Air batteries, achieving a discharge capacity of 414.6 mAh, specific energy of 0.255 mWh, and stable voltage of 0.55 V for 207 hours. The addition of EDTA further enhanced corrosion resistance and system efficiency.

3. Results and Discussion

3.1 Basic Operation of Photovoltaic Cells

In general, solar cells or photovoltaic (PV) cells are devices capable of converting light energy into electrical energy through the photovoltaic effect, where photons striking the surface of a semiconductor release electrons and generate an electric current [19]. One of the alternative technologies being developed is the copper-aluminum (Cu-Al) based photovoltaic cell with a sodium chloride (NaCl) gel electrolyte system, which is considered more cost-effective and environmentally friendly [20].

According to several studies, the use of CuO as the semiconductor layer and aluminum as the conductive electrode offers advantages in terms of material availability and ease of fabrication [21]. The NaCl gel electrolyte plays a significant role in enhancing ionic conductivity and overall system stability [22]. Its gel structure enables more efficient ion movement compared to conventional liquid electrolytes, while also providing protection against moisture and external contamination [23].

However, literature reviews indicate that Cu-Al electrodes still face degradation issues, primarily due to corrosion, oxidation, and microcracks triggered by prolonged exposure to chloride ions [24]. This degradation can reduce system efficiency and shorten the operational lifespan of the solar cells. Therefore, future research should focus on developing mitigation strategies, such as optimizing the gel composition or applying protective coatings to the electrode surfaces [25].

From an economic perspective, several studies have reported that the production cost of Cu-Al solar cells with NaCl gel is significantly lower than conventional silicon-based technologies [26]. Nevertheless, with moderate power conversion efficiency, this technology is considered more suitable for small-scale applications, such as off-grid systems or in remote areas. Large-scale industrial deployment still requires improvements in both efficiency and long-term durability to ensure competitiveness with existing photovoltaic technologies [27].

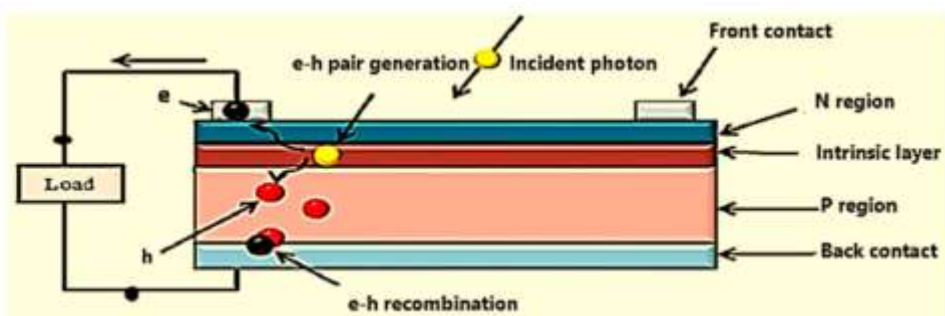

Figure 2. Working principle of PV cells [28]

3.2 Characterization of Materials

The characterization of CuO materials in this study was comprehensively carried out to evaluate the crystal structure, chemical bonding, surface morphology, and potential application of CuO in copper–aluminum photovoltaic systems utilizing sodium chloride (NaCl) gel electrolytes [29]. CuO was synthesized using a two-step combustion method with glycine as an organic fuel. This process was followed by high-temperature calcination at 800°C for 6 hours to obtain high-purity CuO with enhanced crystallinity. Characterization involved Fourier Transform Infrared Spectroscopy (FTIR) for chemical structure analysis and Scanning Electron Microscopy (SEM) for investigating surface morphology and particle size distribution. Both techniques are essential to confirm the microstructural and chemical compatibility of CuO with NaCl gel electrolytes in photovoltaic applications [30].

FTIR analysis of CuO is carried out to identify the functional groups formed during the synthesis process and to ensure the chemical purity of the material [31]. The FTIR spectrum of CuO typically exhibits characteristic absorption bands in the range of 500–600 cm^{-1}, corresponding to the metal–oxygen (Cu–O) bond vibrations, which indicate the successful formation of copper oxide structures [32]. Additional absorption bands appearing in the region of 1400–1600 cm^{-1} or above 3000 cm^{-1} suggest the presence of hydroxyl groups (–OH) or adsorbed water molecules on the material's surface. Excessive amounts of these groups may indicate incomplete synthesis or contamination from the surrounding environment. For solar cell applications, surface purity of CuO is critical, as organic residues or hydroxyl groups can interfere with charge transfer processes and reduce the chemical stability and overall efficiency of the photovoltaic device. Therefore, FTIR serves as a crucial technique to evaluate the chemical structure, purity, and surface quality of CuO before its application in solar cell systems [33].

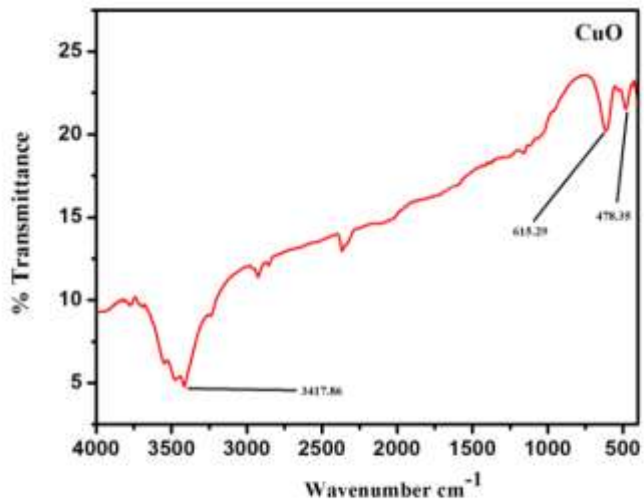

Figure 3. FTIR Analysis Spectrum of CuO [34]

Figure 3. presents the FTIR spectrum of CuO nanoparticles within the range of 400 to 4000 cm^{-1}. FTIR analysis of the synthesized CuO revealed dominant absorption bands in the wavenumber range of 400–700 cm^{-1}, which is characteristic of metal–oxygen vibrations in metal oxide structures [31]. Specifically, two prominent peaks were observed at 478.35 cm^{-1} and 615.29 cm^{-1}, attributed to bending and stretching vibrational modes of the Cu–O bonds within the monoclinic crystal structure of CuO. The presence of these distinct peaks confirms the successful formation of copper oxide with the expected crystallographic structure, consistent with previous literature and JCPDS standards.

In addition to the Cu–O vibrational peaks, a broad absorption band around 3417.86 cm^{-1} was detected, corresponding to O–H stretching vibrations from water molecules adsorbed on the surface of the CuO nanoparticles. This phenomenon is typical for nanomaterials due to their high specific surface area, which increases their affinity for moisture in the surrounding environment. This aspect is critical in the implementation of CuO as an active component in photovoltaic cells, as excessive moisture can affect the electrochemical stability and long-term performance of the system, particularly when used with NaCl gel electrolytes [35].

A CuO surface that is excessively rough or uneven can hinder the interfacial contact between layers, ultimately reducing the overall efficiency of photovoltaic devices [36]. Therefore, SEM observation serves not only as a validation tool for the synthesis process but also provides valuable insight into the potential photovoltaic performance of CuO materials. For instance, SEM images revealing a dense, uniform CuO layer that is free of cracks or voids and adheres strongly to the substrate indicate that the material is likely to produce solar cells with better mechanical stability and higher resistance to degradation in tropical environments. Thus, SEM characterization plays a crucial role in linking the surface morphology quality of CuO to the performance, stability, and operational lifespan of the fabricated solar cells [37].

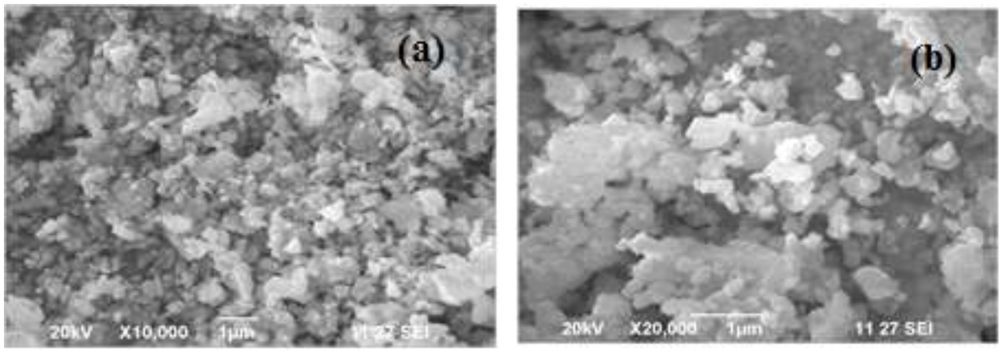

Figure 4. SEM results of CuO [34]

Figure 4. (a & b) displays SEM images of CuO nanoparticles captured at two different magnifications, namely ×10,000 and ×20,000. The surface morphology of CuO was further examined through SEM imaging, which showed that the synthesized particles exhibited a polyhedral structure with rough surfaces. SEM images at magnifications of 10,000× and 20,000× revealed that the primary CuO particles had an average size ranging from 200 to 400 nm. Additionally, a small number of secondary particles with sizes below 100 nm were dispersed among the primary structures. The relatively uniform size distribution indicates a controlled and homogeneous synthesis process, which contributes to the stable dispersion of CuO within NaCl gel electrolytes.

The polyhedral morphology with rough surface textures is expected to significantly enhance the active surface area of CuO, thereby improving heat transfer efficiency and electrochemical interaction within the Cu–Al photovoltaic system [38]. The irregular surface and nanometric particle size promote effective contact between CuO nanoparticles and the gel electrolyte, which is essential for maximizing heat dissipation and minimizing excess heat accumulation in the active area of the solar cell, particularly under high-intensity illumination such as neon light exposure [39].

A controlled particle size distribution, combined with advantageous surface features, provides notable benefits in improving thermal efficiency and material stability. Furthermore, the homogeneous polyhedral morphology may enhance heat absorption and charge transfer performance, directly contributing to increased energy conversion efficiency in Cu–Al photovoltaic systems using NaCl-based gel electrolytes [7].

In conclusion, the FTIR and SEM characterization results confirm that the synthesized CuO nanoparticles exhibit high phase purity, stable chemical structure, and homogeneous polyhedral morphology with particle sizes ranging from the nanometer to submicron scale [40]. These characteristics make CuO highly promising as an active material in the development of copper–aluminum photovoltaic cells, serving both as a cooling agent and a functional layer to enhance energy conversion efficiency and thermal stability, especially when integrated with sodium chloride gel electrolytes under neon lamp illumination [41].

3.3 Characteristics and Physicochemical Properties of Sodium Chloride

Sodium chloride (NaCl) is considered one of the most widely utilized inorganic electrolytes across modern electrochemical systems, including copper-aluminum (Cu-Al) based photovoltaic cells. NaCl is highly favored due to several fundamental advantages, including its abundant availability in nature, low production cost, and excellent chemical stability under varying environmental conditions [7]. These combined properties make NaCl a highly attractive material for renewable energy applications, especially for enhancing the performance and durability of next-generation photovoltaic devices [42].

Table 2. Characteristics of sodium chloride (NaCl)

Property	Value or Description
Chemical Formula	NaCl
Molecular Weight	58.45
Solubility	35.7 gr/100 g
Melting Point	801°C
Boiling Point	1465°C

From a chemical standpoint, NaCl undergoes complete dissociation into sodium ions (Na^+) and chloride ions (Cl^-) when dissolved in aqueous or gel-based media. These free ions play an essential role in enhancing the ionic conductivity of the photovoltaic system [7]. Several studies, have demonstrated that incorporating NaCl in gel form significantly improves ion transport between electrodes, enhances interfacial contact, and reduces internal cell resistance. Consequently, the overall efficiency of light-to-electricity conversion can be improved, with conductivity increases of up to 15% compared to systems using conventional NaCl solutions [43].

Additionally, the use of NaCl gel contributes significantly to improving the stability of Cu-Al electrodes. One of the primary challenges in metallic photovoltaic systems is electrode corrosion and degradation due to environmental exposure, particularly from aggressive Cl^- ions [44]. Interestingly, NaCl gel can form a protective layer over the electrode surface, effectively inhibiting corrosion rates and maintaining electrode structural integrity over prolonged operation. This protective function is especially critical under continuous neon lamp illumination, which simulates real operational conditions for photovoltaic systems, thereby ensuring that energy conversion efficiency is preserved over extended periods [7].

4. Conclusion

Cu-Al photovoltaic cells with NaCl gel electrolyte show promising potential as a low-cost and eco-friendly energy solution. The use of calcined CuO and NaCl gel improves conductivity, electrode stability, and energy conversion efficiency under neon lamp illumination. However, key challenges remain, including electrode corrosion, increased internal resistance in NaCl gel, and limited active surface area of CuO. Further research should focus on optimizing Cu calcination, enhancing NaCl gel stability, and testing system durability under extreme environmental conditions such as high temperatures or humidity.

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