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Review

Optimization of Photovoltaic Cells Using Copper-Aluminium Electrodes and Magnesium Sulfate-Based Gel Electrolytes

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Abstract. Photovoltaic cells are devices that can convert sunlight energy into electrical energy by applying the photovoltaic principle. Indonesia is a country located on the equator that receives a lot of sunlight every year. However, so far the source of electrical energy comes from fossil fuels whose availability is limited. So a material is needed that can improve the performance of photovoltaic cells in producing electrical energy. The purpose of this study was to review the advantages of using Cu-Al electrodes and $MgSO_4$ electrolytes and to find factors that affect the efficiency or performance of photovoltaic cells. This article includes references to articles from 2018 to 2025. The results showed that the use of Cu-Al electrodes and $MgSO_4$ electrolytes can increase cell efficiency. In addition, Cu-Al and $MgSO_4$ are materials that are easy to find and cheap so that they can reduce the cost of making photovoltaic cells compared to other conventional materials that have quite high prices. It is hoped that researchers can utilize this material considering that it has great potential to produce energy in future life.

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1. Introduction

Solar energy is one of the most promising renewable energy sources in the future especially for tropical countries like Indonesia that receive high sunlight intensity throughout the year [1]. In an effort to utilize this potential, solar cell technology continues to be developed to increase efficiency, reduce production costs, and extend service life [2]. One important component in the structure of a solar cell is an electrode that functions to collect and transfer the electrical charge generated by the active material [3]. Various types of materials have been used as electrodes ranging from conventional metals such as copper (Cu) and aluminum (Al) to transparent conductive materials such as silver (Ag) and Indium Tin Oxide (ITO) [4].

Each of these materials has advantages and disadvantages. Copper (Cu) and aluminum (Al) are abundant and relatively inexpensive metals, but have limitations in terms of conductivity and resistance to oxidation when compared to silver (Ag) which offers very high electrical conductivity but at a much more expensive price [5]. Meanwhile, ITO is a transparent conductive material that is widely used in thin film based solar cells because of its ability to conduct electricity while still allowing light to enter the active layer [6]. However, ITO has weaknesses in terms of indium element scarcity, mechanical fragility, and high production costs [7]. Therefore, the selection of electrode materials is a crucial aspect in the design of efficient, affordable, and durable solar cells especially for applications in extreme environments such as Indonesia's tropical climate [8].

In addition to electrodes, electrolytes also play a vital role in several types of solar cells especially in dye-sensitized solar cells (DSSC) [9]. Liquid based electrolytes often experience problems such as evaporation and chemical degradation, so now many researchers are turning their attention to the use of gel-shaped electrolytes, one of which is magnesium sulfate ($MgSO_4$) electrolyte. $MgSO_4$ gel electrolyte has several advantages such as thermal stability, good ion conductivity, and ease of fabrication [10]. However, the long-term use of $MgSO_4$ gel still faces major challenges, especially related to changes in temperature and humidity [11].

High temperature and humidity conditions such as those commonly found in Indonesia can affect the stability of the $MgSO_4$ gel structure. High temperatures can accelerate the degradation of organic components in the gel and increase the rate of solvent evaporation, while high humidity can trigger hygroscopic reactions that change the ion concentration in the electrolyte system. Both of these factors directly affect the efficiency and service life of solar cells [12]. Therefore, in-depth research is needed on the behavior of $MgSO_4$ gel in tropical climate conditions in order to ensure the long-term performance of solar cells in generating electrical energy [13].

Given Indonesia's very favorable geographical position for the application of solar energy technology and the development of efficient, durable, and low-cost solar cells is a strategic necessity. Research on the combination of electrode and electrolyte materials that are in accordance with tropical climate characteristics is very important to support the sustainable energy transition in the country [14]. In this context a study comparing the performance of Cu, Al, Ag, and ITO materials and the use of $MgSO_4$ gel electrolyte is very relevant to be carried out. The results of this study are expected to provide a significant contribution to the development of solar cell technology that is not only technically superior, but also in accordance with the needs and environmental conditions of Indonesia [15].

2. Experimental Section

This research was conducted using a literature review approach. Data sources were obtained from scientific articles, indexed journals and other academic publications relevant to the topic of solar cell optimization, copper-aluminum electrodes (Cu-Al), and magnesium sulfate gel electrolytes ($MgSO_4$). The data collection process was carried out through basic searches of scientific data such as ScienceDirect and Google Scholar using keywords such as "copper-aluminum photovoltaic electrodes", "magnesium sulfate gel electrolytes", and "solar cell optimizers". Each article was analyzed to identify experimental methods, material characterization, solar cell performance results, and optimization approaches used.

The data obtained were then classified based on the focus of the study, the type of material used, parameter efficiency, and the reported technical approach. The analysis was carried out comparatively to identify trends, advantages, limitations, and development opportunities for the Cu-Al/$MgSO_4$ configuration in photovoltaic systems. The results of this literature synthesis are used to formulate conclusions and recommendations for further research. The research chart can be seen in Figure 1.

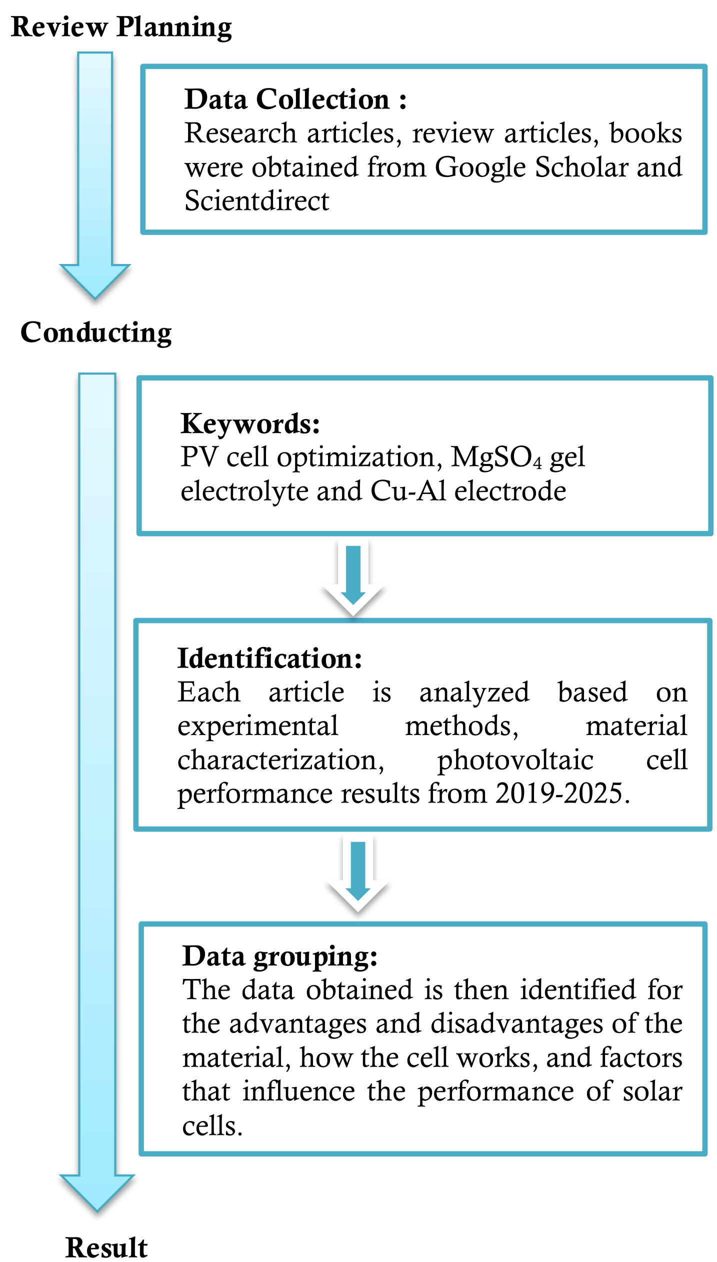

Figure 1. Literature review research flow

Table 1. Comparative studies literature review

No	Tittle	Year	Result
1	$MgSO_4.7H_2O$ filled macro cellular foams: An innovative composite sorbent for thermo-chemical energy storage applications for solar buildings [16]	2018	$MgSO_4$ has good ionic conductivity, is cheap and environmentally friendly making it an attractive material for sustainable energy storage technologies.
2	Synthesis and characterization of Al_2O_3 and CuO nanoparticles into nanofluids for solar panel applications [17]	2019	a. CuO (copper oxide) acts as an additive in nanofluids to improve the cooling efficiency of solar panels. b. b. CuO was chosen because it has high thermal, so it can increase the rate of conductivity heat transfer when used in water-based cooling systems.
3	Modeling of heat transfer and fluid flow in epsom salt ($MgSO_4.7H_2O$) dissociation for thermochemical energy storage [18]	2020	Magnesium sulfate ($MgSO_4 \cdot 7H_2O$) has the property of reversibly absorbing and releasing water through endothermic and exothermic processes, making it suitable for thermochemical energy storage (TCES) applications in solar power systems. This property allows $MgSO_4$ to be used as an efficient and low-cost heat storage material in thermal solar panel systems.
4	Renewable energy systems based on micro-hydro and solar photovoltaic for rural areas: A case study in Yogyakarta, Indonesia [1]	2021	Solar cells are a solution for providing more stable energy, reducing dependence on fossil fuels, and supporting the reduction of carbon emissions.
5	Role of Al doping in morphology and interface of Al-doped ZnO/CuO film for device performance of thin film-based heterojunction solar cells [19]	2024	Al metal can be used as a doping for CuO and ZnO to improve the performance of photovoltaic cells.
6	Enhancing solar cell efficiency: In-situ polymerization with Cu2O@CuO core-shell nanostars [20]	2024	The use of CuO combined with polymers can increase the efficiency of solar cells.
7	Optimization of bifacial PV panels in a residential sector for maximum economic benefits based on load profile [21]	2025	Factors that affect the performance of solar cells namely choosing the right orientation, angle and position of the panel, can increase energy production and reduce energy costs.
8	Thermodynamic study of improved cooling in solar photovoltaic cells using nanofluids with graphite-doped titanium dioxide and aluminum oxide [22]	2025	a. Al has high thermal conductivity b. Al reacts with oxygen to form Al_2O_3 and Al_2O_3 has great potential in improving the performance of photovoltaic solar panels through active cooling systems based on nanofluids

3. Results and Discussion

3.1 Working Principles of Photovoltaic Cells

In a solar cell system that uses copper (Cu) and aluminum (Al) electrodes with magnesium sulfate ($MgSO_4$) based gel electrolyte the working principle of this device starts from the absorption of sunlight by the semiconductor layer. When photons from sunlight hit the semiconductor layer, electrons are excited from the valence band to the conduction band and form electron-hole pairs [23]. The electrons formed are then transferred to the working electrode. In this case copper (Cu) usually functions as a negative charge collector [24]. From there electrons flow through an external circuit to the counter electrode namely aluminum (Al) producing an electric current that can be used by external loads such as LEDs or sensors.

Meanwhile, to maintain the charge balance in the system, the ions in the $MgSO_4$ gel electrolyte play an important role. Mg^{2+} ions move towards the negative electrode (Al), while SO_4^{2-} ions move towards the positive electrode (Cu) creating ionic circulation that allows for continuous charge transfer. This gel-form electrolyte has the advantage of being more stable against evaporation and leakage compared to liquid electrolytes and is more suitable for tropical environments with high humidity such as in Indonesia.

Thus the working circuit of this solar cell involves three main flows: light absorption and charge formation in the semiconductor layer, electron movement through Cu and Al electrodes that produce electric current and the movement of Mg^{2+} and SO_4^{2-} ions in $MgSO_4$ gel that maintains the continuity of the internal circuit. The combination of cheap metal materials (Cu and Al) and non-toxic gel electrolytes makes this system a potential cost-effective alternative for solar energy applications in tropical areas [25].

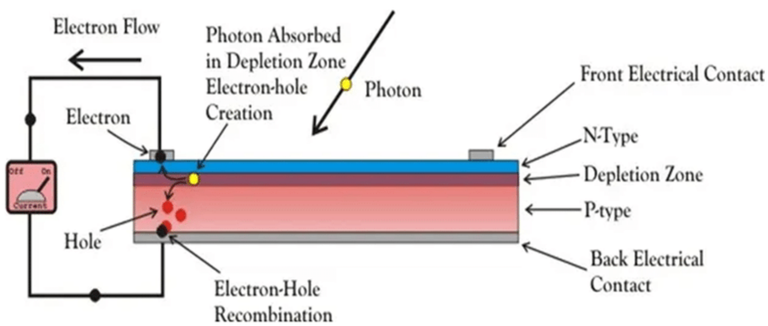

Figure 2. Working principle of PV cells [26]

3.2 Material Characterization

In addition, in photovoltaic cells using semiconductor materials as light absorbing layers [27]. In this study Cu acts as a conductor so it must first be converted into CuO using a thermal oxidation method or heating at high temperatures [28]. The goal is to form a black CuO layer that can be used in photovoltaic cell applications. Furthermore, the CuO that has been formed is characterized using SEM. Analysis of the morphology of the CuO surface using SEM is an important stage in evaluating the quality of semiconductor materials for solar cell applications [29]. Through SEM images, structural characteristics such as particle shape, crystallite size, pore distribution, surface roughness, and the presence of defects such as cracks or particle agglomeration can be observed. In the context of photovoltaic applications, the ideal CuO surface should have a porous or nanorod-shaped structure and a high active surface area in order to maximize sunlight absorption. In addition, uniform and evenly distributed particle sizes will facilitate the charge transport process, reduce electron-hole pair recombination, and increase the efficiency of charge collection by the electrode.

A CuO surface that is too rough or uneven can actually inhibit contact between layers and cause a decrease in efficiency [30]. Therefore, SEM observation not only functions as a validation tool for the synthesis results, but also provides an overview of the potential photovoltaic performance of the CuO material. For example, SEM images showing a compact, gap-free, and strongly attached CuO layer on the substrate indicate that the material is likely to produce solar cells that are more mechanically stable and resistant to tropical environmental degradation. Thus, SEM characterization plays an important role in linking the morphological quality of CuO with the performance and lifetime of the developed solar cells [19].

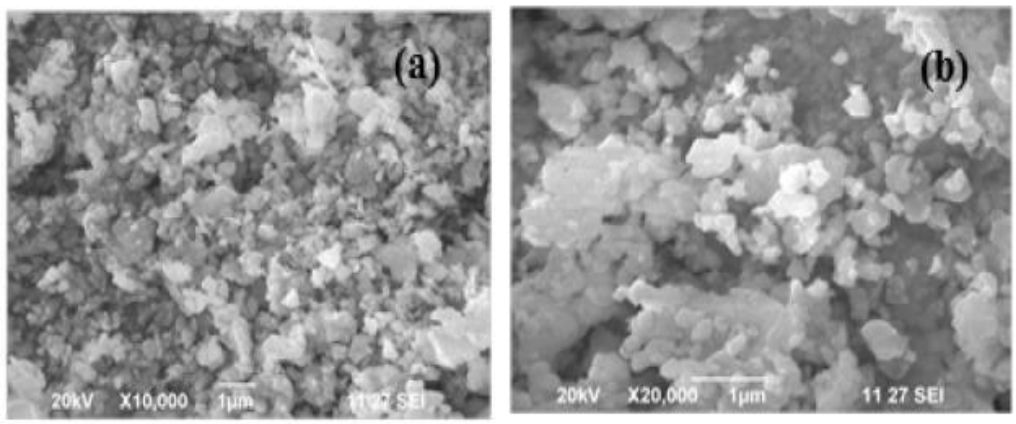

Figure 3. SEM results of CuO [17]

Figure 3. (a&b) shows the SEM photograph of CuO nanoparticles with two different asmagnifications (×10,000 and ×20,000). From the images, it is clearly understood that morphology of CuO nanoparticles shows polyhedral shaped particles along its surface. The primary particles are uniformly distributed throughout materials with the average size range of 200–400 nm and very small quantities of secondary particles have binged here and there with the average size range of less than 100 nm.

FTIR analysis of CuO material was carried out to identify chemical functional groups and molecular bonds formed during the synthesis process [31]. In the context of solar cell applications, FTIR is used to ensure that the chemical structure of CuO has been formed perfectly and does not contain residual compounds or contaminants from precursor materials such as nitrate ions, acetate, or other organic compounds that can affect the stability and performance of photovoltaics. The FTIR spectrum of CuO usually shows a typical absorption band in the 500–600 cm^{-1} region related to the vibration of the metal–oxygen (Cu–O) bond, indicating the formation of a copper oxide structure [32]. Additional bands outside this range such as in the 1400–1600 cm^{-1} region or above 3000 cm^{-1} region, may indicate the presence of hydroxyl groups (–OH) or adsorbed water which if excessive may indicate an incomplete synthesis process or the presence of moisture on the surface of the material. The ideal CuO surface for solar cell applications must be free from organic contaminants or excess hydroxyl groups, because the presence of these groups can interfere with charge transfer and reduce the chemical stability of CuO when exposed to light and moisture for a long time. Therefore, FTIR is very important in assessing the chemical purity and consistency of the oxide structure on the CuO surface.

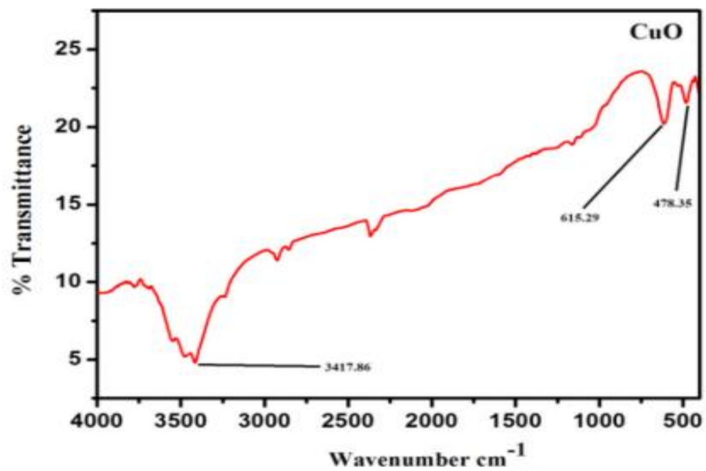

Figure 4. FTIR spectrum of CuO [17]

Figure 4. shows the FTIR spectra for CuO nanoparticles in the range of 400–4000 cm^{-1} . Sample represent a broad extending band in the range 400–700 cm^{-1} , indicates the existence of amorphous structure or disordered defects. The main peaks at 478.35 and 615.29 cm^{-1} from CuO, which could be assigned to the vibration of Cu–O bond formation. The broad absorption peak at around 3417.86 cm^{-1} in CuO is caused by the adsorbed water molecules by the nanoparticles from moisture.

In solar cell development, the selection of electrode materials plays a critical role in determining the efficiency, stability, and production cost of the device [33]. Copper (Cu) and aluminum (Al) are two types of conducting metals that are widely considered as cheap and easy-to-process alternatives to conventional electrodes such as silver (Ag) and indium tin oxide (ITO) [34]. In terms of conductivity Ag has the highest electrical conductivity among all metals, making it very efficient in transporting charges in solar cells [35]. However, the very high price of Ag significantly increases the production cost, especially on a large scale. Meanwhile, ITO which is commonly used as a transparent electrode on the surface of solar cells has high optical transparency and fairly good conductivity, but indium-based ITO is rare and expensive and is prone to mechanical cracking, making it less than ideal for flexible and durable applications in extreme environments.

On the other hand, Cu and Al offer advantages in terms of availability and cost [36]. Both metals are abundant in nature, easily recycled, and compatible with various industrial-scale manufacturing techniques such as sputtering, plating and printing. In terms of conductivity, Cu has excellent performance and is only slightly below Ag making it a strong choice as a charge-collecting electrode in solar cells [37]. Al although more reactive and easily oxidized, also shows high conductivity and is often used as a rear electrode due to its light weight and low cost [38]. However, one of the main challenges in the use of Cu and Al is their resistance to corrosion and oxidation, especially in tropical environmental conditions with high temperatures and extreme humidity such as in Indonesia. Therefore, additional surface treatment or protective coating is needed to improve the stability of the electrode [39].

3.3 Characteristics and Physicochemical Properties of Magnesium Sulfate Gel

Magnesium sulfate ($MgSO_4$) gel has emerged as a promising alternative electrolyte material in photovoltaic applications particularly in dye-sensitized solar cells (DSSCs). The use of gel-based electrolytes such as magnesium sulfate aims to overcome several inherent drawbacks of conventional liquid electrolytes including high volatility, leakage, and chemical degradation that adversely affect the long-term stability of the device. In DSSCs, the electrolyte plays a crucial role in the regeneration of photo-excited dye molecules and the transport of charge carriers between the working and counter electrodes [40]. Magnesium sulfate, an inorganic salt known for its hygroscopic nature and good solubility in water, can form a gel-like medium when combined with solvents and gelling agents such as polyvinyl alcohol (PVA), chitosan, or carbomer. The resulting gel exhibits a semi-solid structure that is mechanically and thermally stable, optically transparent, and ionically conductive properties that make it suitable for use in solar cell systems [41].

Table 2. Characteristics of magnesium sulfate

Characteristic	Value
Specific gratify (Gs)	1,68 g/cm^3
Molecular weight	246,47 g/mol
Melting point	200 C
Colour	White
Water soluble	Complete soluble

One of the key physicochemical properties of magnesium sulfate gel is its ionic conductivity. In this system, Mg^{2+} and SO_4^{2-} ions serve as charge carriers facilitating the transport of electrons from the working electrode to the counter electrode and enabling effective redox cycling. While its ionic conductivity may not yet match that of traditional iodide/triiodide liquid electrolytes commonly used in DSSCs, magnesium sulfate gel shows promise due to its improved stability over extended periods. Furthermore, the gel typically maintains a neutral to slightly acidic pH, which is critical for maintaining the chemical stability of the dye molecules and minimizing corrosion of electrode materials such as titanium dioxide (TiO_2) or indium tin oxide (ITO) [42]. The viscosity of the gel also plays a vital role as it influences ion diffusion within the medium [43]. High viscosity enhances the gel's mechanical stability and resistance to leakage, although it must be carefully optimized to avoid significantly hindering ion mobility which could reduce overall photovoltaic efficiency.

Optically, magnesium sulfate gel is generally transparent allowing efficient light transmission to the photosensitizer layer an essential characteristic for maximizing photon absorption and overall device performance [44]. Additionally, $MgSO_4$ is non-toxic and abundantly available in nature, making it an environmentally friendly and cost-effective choice compared to other electrolytes that contain heavy metals or complex organic compounds. Its non-volatile nature enhances the thermal and photochemical stability of DSSCs by preventing solvent evaporation at elevated temperatures a common issue with liquid electrolytes.

Nevertheless, certain challenges still hinder the widespread adoption of magnesium sulfate gel in DSSC technology. One major limitation is the relatively low energy conversion efficiency compared to that of optimized liquid electrolyte systems [45]. This is primarily due to slower ion mobility within the gel matrix and the absence of highly reactive redox couples like iodide/triiodide, which are crucial for rapid dye regeneration. Consequently, ongoing research is focused on modifying the gel composition or integrating additional redox mediators to enhance its electrochemical performance. Despite these limitations, magnesium sulfate gel remains an attractive candidate for the development of more stable, safe, and sustainable DSSCs, offering notable advantages in environmental compatibility, cost, and material integration.

4. Conclusion

The use of cheap and abundant Cu and Al electrodes combined with $MgSO_4$ gel electrolyte shows great potential in the development of efficient and affordable solar cells. The characterization results show that the formed CuO structure supports light absorption and charge transport, while the $MgSO_4$ gel provides stability against evaporation and humidity. This system is suitable for application in tropical areas such as Indonesia with the potential to be a low-cost solar energy solution that is resistant to extreme environmental conditions.

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