AI-Driven Optimization of Pulsed DC Sputtering for Enhanced Indium Tin Oxide Films

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Article Info

Article history:

Submission July 27, 2025
Revised September 20, 2025
Accepted November 14, 2025
Published November 21, 2025

Keywords:

Indium Tin Oxide
Pulsed DC Magnetron Sputtering
Transparent Conductive Oxides
Heterojunction Silicon Solar Cells
Oxygen Partial Pressure

ABSTRACT

The performance of heterojunction silicon solar cells strongly depends on the quality of the Transparent Conductive Oxide (TCO) layer, particularly Indium Tin Oxide (ITO), which governs both lateral charge transport and optical coupling. Despite its industrial relevance, achieving low-resistivity and high-transmittance ITO at low thermal budgets remains a manufacturing challenge. **This study** aims to identify and optimize the key pulsed DC magnetron sputtering parameters that govern the structural, electrical, and optical properties of ultra-thin ITO films suitable for heterojunction applications. **A systematic** experimental approach was implemented by varying discharge power, oxygen partial pressure, deposition temperature, and post-deposition annealing conditions using an inline industrial sputtering system. **The results** show that moderate discharge power, controlled oxygen incorporation, and substrate temperatures around 180 °C significantly enhance film densification and electron transport. Under the optimized parameter set, the ITO films achieved low resistivity in the range of $(4.6–5) \times 10^{-4}\ \Omega \cdot \text{cm}$ and visible-light transmittance above 90%, while annealing at 160 °C further reduced defect density and stabilized electrical performance. **These findings** demonstrate that high-quality ITO can be produced within the thermal constraints of heterojunction silicon technologies and provide a robust foundation for integration into automated or AI-assisted sputtering control frameworks. Overall, this work supports the development of scalable, energy-efficient, and industrially viable fabrication routes for next-generation photovoltaic devices.

DOI: https://doi.org/10.33050/italic.v4i1.931

1. INTRODUCTION

Amorphous or crystalline silicon heterojunction (HJT) solar cells employ crystalline silicon wafers as the primary charge transport medium, while thin hydrogenated amorphous silicon layers are deposited using plasma-based processes to achieve surface passivation and junction formation [1, 2]. The deposition temperature of these amorphous layers typically remains below 200 °C, allowing HJT technology to maintain a low thermal budget and enabling compatibility with high throughput industrial fabrication. Recent reports, such as those from SANYO (Japan), demonstrate conversion efficiencies up to 23.7% (Voc = 0.745 V, Jsc

= 39.38 mA/cm^2, FF = 80.9 %, cell area = 100.7 cm^2), highlighting the strong performance potential of this architecture [3, 4].

A TCO layer is essential in HJT structures to support lateral carrier transport while simultaneously functioning as an Anti Reflective Coating (ARC). Among various TCO materials, ITO remains the dominant choice due to its excellent electrical conductivity and high optical transmittance [5, 6]. Magnetron sputtering either Direct Current (DC), pulsed DC, or Radio Frequency (RF) is widely adopted for TCO deposition because of its process stability, controllable plasma characteristics, and ability to produce uniform thin films across large area substrates [7, 8]. Pulsed DC sputtering, in particular, offers advantages in target utilization efficiency and reduced arcing, making it suitable for industrial scale ITO fabrication.

From a national policy perspective, the Indonesian Government has issued MEMR Regulation No. 2 of 2024 governing rooftop solar photovoltaic systems connected to licensed public-supply electricity networks. This regulation strengthens the framework for distributed solar deployment by removing previous capacity limits, simplifying grid interconnection procedures, and encouraging wider adoption of PV technologies across residential, commercial, and industrial sectors [9, 10]. Such regulatory support reinforces the industrial relevance of high performance TCO fabrication including optimized ITO sputtering because the demand for efficient photovoltaic components directly increases as rooftop solar deployment accelerates across the country [11].

In addition to aligning with national policy developments, this research contributes to global sustainability frameworks, particularly the United Nations Sustainable Development Goals (SDGs). The optimization of ITO thin-film fabrication directly supports SDG 7 (Affordable and Clean Energy) by enabling higher photovoltaic efficiency through improved optical transmittance and reduced resistivity [12, 13]. The work also advances SDG 9 (Industry, Innovation, and Infrastructure) by integrating advanced thin-film engineering with intelligent manufacturing principles, such as data-driven process optimization and potential AI-assisted sputtering control [14, 15]. Furthermore, the enhancement of transparent conductive oxide performance contributes to SDG 13 (Climate Action) by supporting large scale renewable energy adoption and reducing dependence on fossil based electricity generation. Collectively, these contributions position optimized ITO sputtering not merely as a materials-engineering improvement but as a strategic enabler of sustainable energy-transition targets [16, 17].

The objective of this study is to optimize sputtering parameters and post-deposition annealing conditions using an inline pulsed DC magnetron sputtering system to produce ITO thin films with high conductivity and high optical transmittance suitable for HJT solar cells [18, 19]. Beyond experimental optimization, this work aligns with emerging intelligent manufacturing trends by demonstrating how identified parametric relationships—such as those involving discharge power, oxygen partial pressure, and substrate temperature—can serve as predictive features for AI-driven process control [20, 21]. Integrating these experimentally validated trends into machine learning based sputtering controllers would enable real-time adaptive tuning, minimize process drift, and increase reproducibility in large scale photovoltaic production. Thus, the contributions of this research extend beyond material characterization, offering a pathway toward AI-enhanced TCO fabrication workflows for next-generation solar technologies [22, 23].

2. LITERATURE REVIEW

This section provides a consolidated overview of prior research related to Transparent Conductive Oxides (TCOs), sputtering technologies, and critical process parameters influencing ITO film performance. The objective is to establish a coherent theoretical foundation for understanding how deposition conditions affect optical and electrical characteristics in heterojunction silicon solar cells, and to clarify the research gap that motivates the present work [24, 25].

2.1. Transparent Conductive Oxides for HJT Solar Cells

Transparent conductive oxides serve as essential components in HJT solar cells, enabling lateral charge transport and simultaneously functioning as anti-reflective coatings. Among the various TCO materials, indium tin oxide has remained the benchmark due to its low resistivity, high visible light transmittance, and compatibility with low temperature processing required for amorphous or crystalline silicon interfaces [26, 27]. These advantages make ITO an optimal choice for maintaining surface passivation quality under the typical thermal limitations of HJT fabrication.

Comparative studies with alternative materials such as Aluminum–doped Zinc Oxide (AZO) and Fluorine–doped Tin Oxide (FTO) reveal that although these options offer lower material cost, they often exhibit reduced conductivity or weaker environmental stability, particularly at thicknesses below 100 nm where optical and electrical trade–offs become pronounced [28, 29]. Consequently, ITO continues to dominate in high-efficiency photovoltaic architectures due to its superior balance of optical and electronic performance. The effectiveness of ITO, however, is strongly determined by its deposition method and the microstructural properties that arise during film growth.

2.2. Magnetron Sputtering Methods for ITO Thin Films

Magnetron sputtering is widely recognized as the most effective deposition method for high quality ITO films in industrial photovoltaic production. DC and RF sputtering have been extensively utilized due to their stable plasma generation, high material utilization, and uniform thickness distribution across large substrates [30, 31]. Although RF sputtering provides excellent uniformity, it often yields lower deposition rates, which can limit throughput in mass production environments.

Pulsed DC magnetron sputtering has emerged as an advanced alternative, offering high deposition stability, reduced arcing, and improved process control [32, 33]. The periodic switching of polarity suppresses charge accumulation on the target surface, allowing more consistent plasma behavior and enabling higher deposition rates. Additionally, the energetic ion bombardment inherent to pulsed DC sputtering promotes improved film densification, reduced structural defects, and enhanced crystallinity. These attributes collectively lead to lower resistivity and higher transparency, making pulsed DC sputtering an attractive method for high volume HJT solar cell manufacturing.

2.3. Key Parameters Affecting ITO Film Performance

The electrical and optical characteristics of ITO films are highly sensitive to oxygen stoichiometry, substrate temperature, and post deposition annealing. Oxygen vacancies serve as shallow donor states, increasing carrier concentration and contributing to low resistivity [34, 35]. However, excessive vacancy formation can induce free carrier absorption, thereby reducing transparency. Conversely, oxygen rich environments suppress carrier density and elevate resistivity, creating a narrow optimization window for photovoltaic applications.

Substrate temperature is another critical variable affecting adatom mobility and film microstructure. Elevated temperatures enhance grain growth and reduce grain boundary scattering, yet HJT manufacturing imposes strict thermal limits to preserve the passivation of amorphous silicon layers [36, 37]. As a result, achieving optimal properties at moderate temperatures remains an active research challenge. Post deposition annealing has been shown to further improve carrier mobility, stabilize vacancy distribution, and enhance optical transmittance without compromising interface integrity [38].

Recent advancements in intelligent manufacturing have introduced AI-driven predictive modeling and real-time process optimization for sputtering systems. Data driven control strategies can map sputtering conditions to resulting film properties, enabling adaptive tuning of discharge power, oxygen partial pressure, and substrate temperature [39]. Such developments align with the increasing integration of automated decision systems in photovoltaic production lines and highlight the relevance of intelligent process control in the optimization framework adopted in this study.

3. METHODOLOGY

This study adopted a systematic experimental framework to investigate how key sputtering parameters affect the electrical and optical performance of ITO thin films. All experiments were conducted using an inline pulsed DC magnetron sputtering system, where individual parameters were varied independently to isolate their effects on film properties. The methodology comprises the system configuration, material preparation, deposition procedures, and post-deposition characterization techniques, as detailed below.

3.1. System and Materials

The inline pulsed DC magnetron sputtering system (FHR, Germany) supports high-throughput deposition over substrate areas up to 30×40 cm^2, enabling simultaneous processing of six 125×125 mm^2 wafers. Pulsed DC excitation suppresses electrical arcing and ensures stable plasma behavior, which is beneficial for producing uniform industrial-scale TCO films [40].

Prior to deposition, the chamber was evacuated to a base pressure of (2–3) × 10^6 mbar to minimize contamination. Each deposition cycle maintained the substrate within the plasma region for approximately 45 s, resulting in a cumulative deposition time of 135 s over three cycles. These conditions were kept constant to ensure reproducibility.

The sputtering line consists of separate chambers for metallic and TCO deposition. Two TCO materials are available in the system: AZO with dual rotatable targets and ITO with a planar target. This study utilized a planar ITO target composed of In_2O_3:Sn (90:10 wt.%, 99.99% purity), with dimensions of 54 × 9 cm^2 and a target substrate distance of 80 mm. The power supply permits a maximum discharge power of 10 kW, while a multi zone heater provides substrate temperatures up to 350 °C. Gas flow controllers regulate O_2, Ar, and N_2 with high precision during processing.

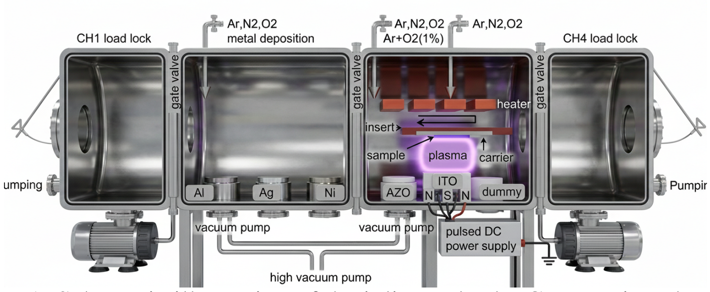

Figure 1. Schematic illustration of the inline pulsed DC sputtering chamber.

Glass slides (2.5 × 7.6 cm^2, Menzel Gläser, Germany) were used as substrates. Each sample underwent a sequential cleaning process with isopropanol and acetone, followed by nitrogen drying. The substrates were fixed within a uniform deposition zone using Kapton tape. After mounting onto a stainless-steel holder, the samples were introduced into the deposition chamber via a load-lock system. During sputtering, the substrate carrier oscillated laterally to ensure uniform thickness distribution, as illustrated in Fig. 1.

3.2. Experimental Description and Characterization Methods

A single-variable optimization strategy was implemented, where one sputtering parameter was varied at a time while all others remained constant. The optimized values obtained at each stage were used as inputs for subsequent refinements. Four major parameters were examined: discharge power, chamber pressure, oxygen partial pressure, and substrate temperature [41].

To minimize potential ion-induced damage to the amorphous silicon layers used in heterojunction solar cells, relatively low power densities were selected. In this study, discharge powers ranging from 250 to 2500 W were applied, corresponding to power densities of 0.5–5 W/cm^2. Chamber pressure was adjusted via mass flow controllers, with operational limits of 115 sccm for Ar and 3.5 sccm for O_2. Due to the high-vacuum conditions, radiative heating dominated thermal transfer, resulting in a maximum substrate temperature difference of approximately 150 °C.

Other process variables including pulse frequency (50 kHz), carrier motion speed (12 mm/s), number of deposition cycles (three), and oscillation amplitude (600 mm) were held constant throughout all experiments. For each sputtering condition, two samples were produced: one as-deposited and one subjected to post-deposition annealing at 160 °C for three hours in ambient air.

Film electrical properties were assessed using a four-point probe system (CRESBOX, NAPSON, Japan). Thickness measurements were performed using a stylus profiler (DEKTAK 150, VEECO, USA) by evaluating step heights at masked regions. Optical characterization was carried out using a UV–VIS–NIR spectrophotometer (PerkinElmer Lambda 950, USA), while the average visible transmittance (390–750 nm) was obtained with a haze meter (Haze-gard Plus, BYK-Gardner, Germany). All measurements were conducted for both as-deposited and annealed samples.

4. RESULTS AND DISCUSSION

This section presents the experimental findings obtained from the optimization of sputtering parameters and post deposition treatments applied to the ITO thin films. The discussion highlights how each parameter influences resistivity, optical transmittance, and growth rate, supported by the figures provided in the following subsections.

4.1. Optimization of Sputtering Parameters

A comprehensive optimization procedure was conducted to evaluate the influence of discharge power, gas flow rates, and oxygen partial pressure on the electrical and optical performance of the ITO films. These parameters directly affect growth kinetics, defect concentrations, and microstructural evolution. The overall trends obtained from the measurements are summarized in Figs. 2–6, which form the quantitative foundation of the analysis. Before discussing each parameter in detail, Fig. 2 provides an overview of how discharge power affects resistivity and growth rate. This figure establishes the baseline sputtering power selected for the subsequent optimization stages.

As shown in Fig. 2(a), increasing the pulsed DC power significantly reduces film resistivity. Post-deposition annealing further decreases resistivity and minimizes sample-to-sample variation. Figure 2(b) shows that the growth rate increases almost linearly with increasing power, indicating enhanced sputtering yield. Error bars, based on three repeated measurements, demonstrate the reliability of the extracted data. Since the TCO layer is deposited directly on the amorphous silicon layer of heterojunction solar cells, excessive ion bombardment may degrade surface passivation. To avoid this effect, a moderate discharge power of 1500 W (equivalent to a power density of 3 W/cm^2) was selected for subsequent experiments.

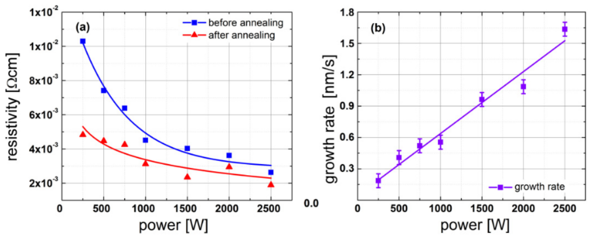

Figure 2. (a) Resistivity of ITO as a function of discharge power. (b) Growth rate as a function of discharge power. Error bars represent the standard deviation of repeated measurements.

The results in Fig. 2 clearly indicate that discharge power strongly influences electron-transport characteristics. Higher power increases ionization efficiency, enabling sputtered atoms to form denser and more conductive films.

Figure 3 illustrates the effect of argon flow rate on resistivity and transmittance. Lower chamber pressure, corresponding to reduced Ar flow, improves both conductivity and optical transparency. After annealing at 160 °C for three hours, resistivity decreases by approximately 20%. This improvement is attributed to the formation and stabilization of oxygen vacancies during annealing, which increase carrier concentration and mobility.

Within the examined range, chamber pressure produces only minor changes in growth rate (approximately 0.92 nm/s). A slight reduction in transmittance at higher Ar flow rates is observed, likely due to increased plasma scattering. Based on these results, an Ar flow rate of 125 sccm (corresponding to a pressure of approximately 1.7×10^{-6} bar) was chosen for subsequent experiments.

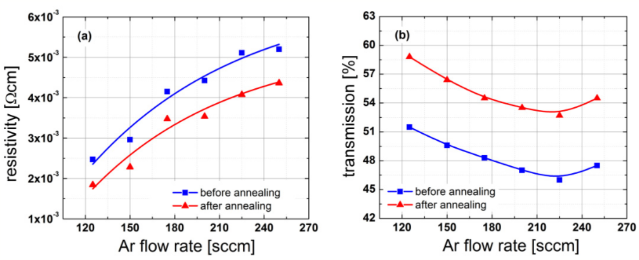

Figure 3. (a) Resistivity of ITO as a function of Ar flow rate. (b) Transmittance of ITO as a function of Ar flow rate.

The trends in Fig. 3 highlight the importance of maintaining a stable chamber pressure to achieve high performance ITO films. Lower pressure increases the mean free path of sputtered species, enhancing overall deposition efficiency.

After optimizing chamber pressure, the total gas flow was fixed at 125 sccm while varying the oxygen partial pressure. As shown in Fig. 4, introducing 3.2% oxygen significantly increases visible-range transmittance (from 51% to 89%) and reduces resistivity from $2.5 \times 10^{-3}\,\Omega \cdot \mathrm{cm}$ to $1.0 \times 10^{-3}\,\Omega \cdot \mathrm{cm}$. These results highlight the strong sensitivity of ITO to oxygen stoichiometry. An optimal concentration of oxygen vacancies improves conductivity while maintaining high optical transparency, whereas excessive oxygen reduces carrier density and increases resistivity.

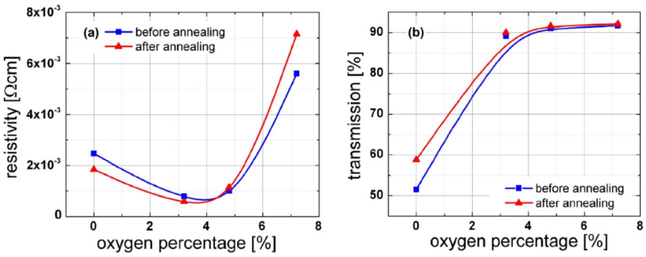

Figure 4. (a) Resistivity of ITO under different oxygen ratios. (b) Visible-range transmittance under the same conditions.

The results in Fig. 4 confirm that precise oxygen control is essential for optimizing both electrical and optical performance in ITO thin films.

Figure 5 presents the transmittance spectra for three oxygen ratios before and after annealing. Annealing increases transmittance in the 300–500 nm region, indicating improved structural ordering. At 3.2% oxygen, transmittance also increases near 1000 nm due to reduced scattering. The observed reduction in transmittance in the 2000–2500 nm range may correspond to enhanced free-carrier absorption associated with vacancy formation.

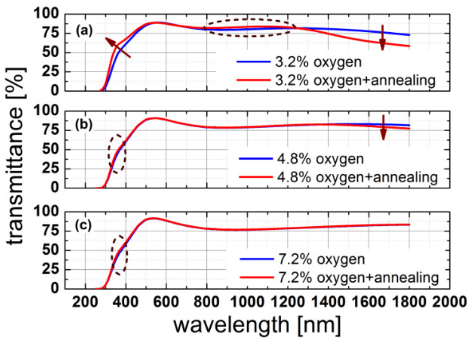

Figure 5. Transmittance spectra for oxygen ratios of (a) 3.2%, (b) 4.8%, and (c) 7.2%, before and after annealing.

The spectral characteristics shown in Fig. 5 reinforce the conclusion that moderate oxygen ratios produce the best trade off between vacancy-enhanced conductivity and optical clarity.

Figure 6 shows the effect of substrate temperature on film performance. While room temperature deposition yields acceptable results, increasing deposition temperature substantially improves both conductivity and transparency. The optimal performance appears at approximately 180 °C, where visible range transmittance reaches nearly 90% and resistivity is minimized. These improvements are attributed to enhanced adatom mobility at elevated temperatures, which promotes a denser and more uniform microstructure. Post annealing further stabilizes the electrical properties.

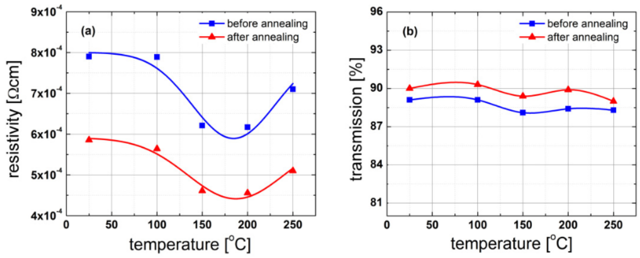

Figure 6. (a) Resistivity of ITO as a function of deposition temperature. (b) Visible-range transmittance of the same samples.

The results in Fig. 6 demonstrate that moderate substrate heating enables superior electrical and optical performance while remaining within the thermal constraints of heterojunction solar cell fabrication. Annealing at 160 °C for three hours consistently improves conductivity across most samples. Films deposited under oxygen deficient conditions exhibit higher resistivity due to non-stoichiometric composition, whereas excessive oxygen increases resistivity via enhanced grain boundary scattering. Despite these variations, all annealed films show improved optical transmittance, contributing favorably to photocurrent generation. These performance gains are attributed to optimized vacancy concentration, improved structural uniformity, and reduced defect states across the film.

5. MANAGERIAL IMPLICATIONS

The findings of this study offer several strategic and operational implications for managers, process engineers, and decision makers involved in photovoltaic manufacturing and thin-film production. First, the identification of optimal sputtering conditions particularly discharge power, oxygen partial pressure, and substrate temperature provides a clear and actionable guideline for improving throughput and ensuring uniform ITO film quality in industrial settings. By adopting the optimized parameter set presented in this research, manufacturers can minimize process variability, reduce defect formation, and lower overall energy consumption, ultimately supporting higher production yield and more predictable device performance.

Second, the demonstrated advantages of low temperature post deposition annealing highlight the importance of integrating controlled thermal treatment into large scale fabrication workflows. Since annealing at moderate temperatures significantly enhances both electrical conductivity and optical transparency, production managers can incorporate this step without increasing the thermal budget or requiring equipment redesign. This makes the annealing strategy cost effective and compatible with existing heterojunction silicon solar cell manufacturing lines, supporting improved efficiency without additional capital expenditure.

Third, the empirical trends derived from the experiments can be directly embedded into intelligent process control frameworks. Managers overseeing automation and digitalization can leverage these correlations to develop AI-assisted sputtering systems capable of real-time parameter tuning, predictive quality estimation, and early detection of process drift. Such data-driven control enhances long-term stability, reduces variability across production batches, and facilitates proactive maintenance planning, aligning with modern smart-manufacturing paradigms.

Overall, these managerial implications emphasize that optimized pulsed DC magnetron sputtering not only improves the technical quality of ITO films but also strengthens operational efficiency and manufacturing sustainability. The integration of optimized process parameters, low-temperature annealing, and AI-enabled control systems provides a comprehensive pathway for enhancing scalability, reliability, and competitiveness within next-generation photovoltaic production.

6. CONCLUSION

This study systematically examined the influence of pulsed DC magnetron sputtering parameters on the structural, electrical, and optical characteristics of ITO thin films intended for heterojunction silicon solar cells. The results confirm that discharge power, chamber pressure, oxygen partial pressure, and substrate temperature each play a critical role in determining growth rate, resistivity, and visible range transmittance. Under the optimized conditions achieved in this work, the ITO films exhibited low resistivity in the range of

$(4.6–5) \times 10^{-4}\,\Omega \cdot \mathrm{cm}$ and transmittance approaching 90%, demonstrating the suitability of the deposition configuration for high-performance transparent conductive oxide layers.

The mechanistic analysis reveals that improvements in conductivity are primarily driven by the controlled formation of oxygen vacancies, which enhance carrier concentration and support efficient electron transport. Post-deposition annealing at 160 °C further contributes to reduced defect density and improved structural ordering, strengthening both optical clarity and electrical uniformity across all optimized conditions.

Overall, the findings demonstrate that high quality ITO films can be produced using relatively low thermal budgets, ensuring compatibility with temperature sensitive heterojunction solar cell architectures. The parameter relationships established in this study provide a robust foundation for integration into automated or AI-assisted sputtering control systems, supporting real-time process optimization and scalable industrial deployment. Collectively, the results advance the development of reliable and reproducible fabrication pathways for next-generation photovoltaic technologies.

7. DECLARATIONS

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7.2. Author Contributions

Conceptualization: KV; Methodology: KV and HC; Software: KV; Validation: HH and AR; Formal Analysis: HC and AR; Investigation: KV; Resources: KV; Data Curation: HH; Writing Original Draft Preparation: KV and HH; Writing Review and Editing: HC and AR; Visualization: KV and HC; All authors, HH, HC, KV, and AR, have read and agreed to the published version of the manuscript.

7.3. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.4. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

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