Investigation of Zinc Cobaltite ($ZnCo_2O_4$) as a Hole Transport Layer for Perovskite Solar Cells: Implications for Renewable-Energy Research and Innovation

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ABSTRACT

This study investigates Zinc Cobaltite ($ZnCo_2O_4$) as a potential hole transport layer (HTL) for perovskite solar cells (PSCs) to address the long-term performance degradation observed in conventional HTL materials. Owing to its high stability, wide bandgap, and favorable charge-transport characteristics, $ZnCo_2O_4$ offers strong potential for efficient carrier extraction and transport in PSC architectures. The HTL plays a critical role in selectively extracting and transferring positive charge carriers (holes) to the anode while maintaining overall device stability. In this work, $ZnCo_2O_4$-based PSCs were simulated using the GPVDM software, and the Taguchi optimization method was employed to determine the optimal design parameters for achieving maximum power conversion efficiency (PCE). The key parameters considered include HTL thickness, operating temperature, and bandgap energy. Simulation results reveal that a $ZnCo_2O_4$ thickness of 200 nm yields a PCE of 28.25% using GPVDM. Through Taguchi optimization, the highest PCE of 32.23% was achieved with an optimized configuration comprising a 300 nm $ZnCo_2O_4$ layer, 300 K temperature, 2.0 eV bandgap, and mobility factors of 9.14×10^{-6} cm^2 V^{-1} s^{-1} for both electrons and holes. These findings demonstrate that $ZnCo_2O_4$ is a promising HTL candidate for high-efficiency and thermally stable PSCs. Further experimental validation and interface engineering could enhance its performance and enable its integration into next-generation perovskite photovoltaic devices.

Keywords—Zinc Cobaltite, Hole Transport Layer, GPVDM, Taguchi method

INTRODUCTION

In recent decades, the escalating global demand for renewable and clean energy has made solar power a central pillar of sustainable electricity generation strategies [1]. Among emerging photovoltaic technologies, perovskite solar cells (PSCs) have attracted substantial interest thanks to their rapidly improving power conversion efficiencies, solution-processable fabrication, and tunable optoelectronic properties [2], [3]. However, key challenges include device longevity as well as the cost and durability of interface layers, particularly the hole transport layer (HTL) [4].

To address these challenges, this study investigates Zinc Cobaltite ($ZnCo_2O_4$) as a candidate HTL. $ZnCo_2O_4$ brings advantages such as strong chemical and thermal stability, favorable valence band alignment with perovskite absorbers, and potentially higher hole-transport capability compared to conventional HTLs like

PEDOT:PSS and spiro-OMeTAD [5], [6]. Recent experimental work has shown that PSCs employing $ZnCo_2O_4$ nanoparticle HTLs can outperform PEDOT:PSS-based devices in long-term stability without sacrificing efficiency [5].

We adopt the General-purpose Photovoltaic Device Model (GPVDM) simulation platform to model cell architectures incorporating $ZnCo_2O_4$ as the HTL. GPVDM is an open, freely available (open-source) simulation tool capable of simulating optoelectronic behavior, including drift-diffusion, trapping, recombination, and optical propagation—in disordered materials such as perovskites and organic semiconductors [7]. Indeed, numerous studies have used GPVDM to explore thickness effects, carrier mobility impacts, and device optimization in perovskite and organic solar cells [8], [9]. Within this framework, we systematically vary HTL thickness, operating temperature, and bandgap in a design-of-experiments approach to seek optimal power conversion efficiency (PCE) and durability. Comparative benchmarking against conventional HTLs will then validate the merits of $ZnCo_2O_4$ in achieving a balance of cost-effectiveness, stability, and charge-transport performance.

Device Structure

Nowadays, the third generation of solar cells has been proven to be the future method to generate electricity using solar power. Due to their high PCE and suitability for scalable procedures, perovskite solar cells, a new third generation solar cell look to have a very strong possibility of helping to scale up solar energy production. In no other period in the history of solar cell research has the PCE been increased at such a quick rate as it has been for perovskite solar cells. Perovskites are considered as ideal photovoltaic materials in solar cells due to their high absorption in the visible spectrum, long carrier diffusion length, high carrier mobility, low exciton binding energy, tunable bandgaps by exchanging atomic composition, large area production and low cost owing to solution process-ability [5].

The effectiveness and lifetime of perovskite solar cells depend on the stability of the HTL. The extraction of positive charge carriers (holes) from the perovskite layer and their transportation to the anode are accomplished by the HTL, a crucial part of the device construction. Because it may eventually have an impact on the device's general effectiveness and performance, the HTL's reliability is crucial.

There are several challenges with HTL in perovskite solar cells, including the possibility of degradation in the presence of oxygen and moisture. This might lead to a decline in the device's performance over time. Experts have been examining various materials and manufacturing techniques to improve the stability and lifespan of HTLs. Because of its advantages, such as high hole mobility, broad band gap, and straightforward solvent treatment technique, inorganic p-type semiconductor materials have the potential to replace organic hole transport materials. Table I shows the comparison between $ZnCO_2O_4$ with other HTL materials in terms of stability. The PCE of perovskite solar cells is directly influenced by their stability. Due to its high PCE potential, perovskite solar cells have attracted interest, but their stability is still a problem that has to be solved for commercial viability.

Table I Comparison Stability of Various Material as Hole Transport Layer in Perovskite Solar Cell

HTL materials	Stability
Zinc Cobaltite, $ZnCO_2O_4$	Exhibits strong hole transport capability, wide optical bandgap, and good solution processability. $ZnCo_2O_4$ has been reported as a promising alternative HTL due to its high stability and applicability in both photoelectrochemical and photovoltaic systems [5].
Copper Galium Oxide, CuGaO2	Demonstrates excellent thermal stability and superior resistance to moisture-induced corrosion, making it a robust inorganic HTL [10].
Copper(I) Iodide, CuI	Possesses higher conductivity than spiro-OMeTAD, enhancing the device's fill factor and overall PCE; considered a strong inorganic HTL candidate [11].

PEDOT:PSS	Prone to corroding transparent conducting oxides (e.g., FTO), which limits long-term stability. Its high acidity and large interfacial energy barrier reduce Voc, Jsc, and overall PCE [5], [12].The photovoltaic performance including VOC, short circuit current (JSC) and stability are relatively low because of the huge energy barrier between PEDOT:PSS and the perovskite layers as well as the high acidity of the PEDOT:PSS solution.[12]
Spiro-OMeTAD	Offers good film-forming properties but exhibits low intrinsic hole mobility (2×10^{-4} cm^2 V^{-1} s^{-1}), leading to higher resistive losses [12].
Poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine], PTAA	Functions effectively only with dopant additives, which can induce instability under long-term operation [12].
Poly(3-hexylthiophene), P3HT	Displays high carrier mobility, a suitable bandgap matching the solar spectrum, and low cost, though less stable than inorganic alternatives [12]

HTL efficiency

As a hole transport material, each material has very own advantages that only that material has. This efficiency is based on how much solar energy can be absorbed and how much electricity can be gained from it. There are so many materials that have been researched so far, and Zinc Cobaltite is the new one on that list. Table II shows the PCE of various materials that has been used as HTL in PSC from another research since 2019.

Table II Comparison PCE of various material as hole transport layer in perovskite solar cell

Hole Transport Layer	Best PCE (%)	Ref
ZnCO2O4 Nps	11.78	[5]
Nickel Oxide,Nio	15.65	[13]
Spiro-OMeTAD	11.9	[14]
Kesterite Czts Nps	6.0	[15]
Cuox Fs	13.35	[16]
P3HT	16.7	[17]
CuI	7.5	[18]
CuSCN	18.0	[19]
PTAA	18.11	[20]
CuGaO2	16.2	[21]
CuCrO2	20.54	[22]
CuPc	13.65	[23]
MoS2	8.3	[24]
CuAlO2	19.82	[25]
Pedot:Pss Flm	11.8	[26]

METHODOLOGY

This section describes the simulation and optimization procedures used to evaluate $ZnCo_2O_4$ as a HTL in PSCs. The methodology consists of two main stages: the device simulation using GPVDM and Taguchi optimization phase.

Material Registration and Simulation Setup

Because $ZnCo_2O_4$ is not included in the default GPVDM material library, the first step involved manually registering its electrical and optical parameters. These parameters included bandgap energy, electron and hole mobilities, affinity, and relative permittivity. After successful registration, the software was used to simulate the PSC device structure incorporating $ZnCo_2O_4$ as the HTL.

Each simulation was conducted with fixed ETL and absorber materials to ensure valid comparisons across different HTLs. The PSC structure comprised fluorine-doped tin oxide (FTO) as the anode, titanium dioxide (TiO_2) as the ETL, cesium lead iodide ($CsPbI_3$) as the perovskite absorber, $ZnCo_2O_4$ as the HTL, and gold (Au) as the cathode, as illustrated in Fig. 2.

Multiple simulations were performed by varying the $ZnCo_2O_4$ thickness from 50 nm to 500 nm in 25 nm increments. After each run, the PCE, fill factor (FF), open-circuit voltage (Voc), and short-circuit current density (Jsc) were extracted. These data were then analyzed to determine the most suitable HTL thickness before proceeding to parameter optimization.

Taguchi Optimization Phase

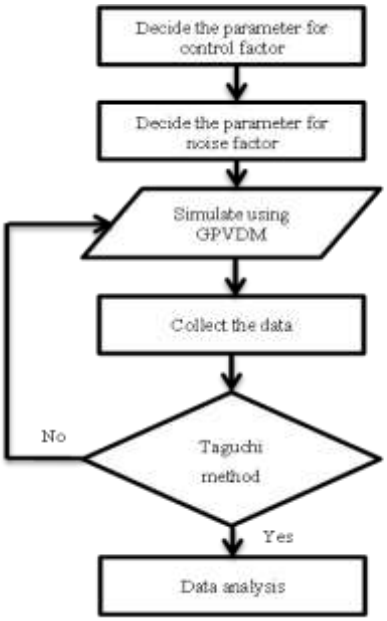
To identify the parameters that most significantly influence the PCE, the Taguchi method was implemented using an L9 (3^3) orthogonal array. This approach minimizes the number of simulations while maintaining a statistically valid evaluation of factor interactions. Three control factors and two noise factors were considered. The control factors are (1) Thickness of $ZnCo_2O_4$ HTL (Factor A); (2) Operating temperature (Factor B); and (3) Bandgap energy of $ZnCo_2O_4$ (Factor C). The noise factors are (1) Hole mobility; and (2) Electron mobility

Each factor was varied at three levels based on preliminary simulations. The Taguchi L9 array produced nine unique test conditions, which were simulated in GPVDM under identical illumination and boundary conditions.

For each simulation, PCE, Voc, Jsc, and FF were recorded. The resulting data were analyzed using the signal-to-noise (S/N) ratio under the "larger-the-better" criterion to identify the factor level combinations that maximize efficiency. An analysis of variance (ANOVA) was subsequently performed to quantify the contribution of each factor to the total PCE variance.

A flowchart of the Taguchi phase is shown in Fig. 1, outlining the workflow from factor selection to confirmation testing.

Fig. 1 Flowchart of the Taguchi optimization phase for $ZnCo_2O_4$-based perovskite solar cells.



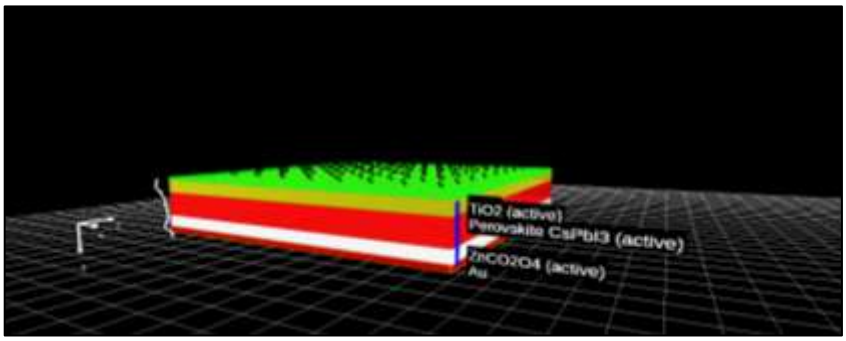
Device Simulation Using GPVDM

GPVDM is an open-source software platform for modeling the electrical and optical behavior of thin-film and disordered-semiconductor devices. Unlike equilibrium-based models, GPVDM applies a non-equilibrium carrier-transport formalism that accurately describes trapped carrier dynamics using the Shockley–Read–Hall recombination model.

This feature enables reliable simulation of PSCs with complex interfaces and defect states. The software computes the current–voltage (I–V) response, carrier densities, recombination rates, and electric-field distributions under steady-state or transient illumination.

The simulated PSC stack configuration is depicted in Fig. 2, showing the device layers of FTO/TiO_2/$CsPbI_3$/$ZnCo_2O_4$/Au. The input parameters included the material bandgap, electron affinity, relative permittivity, and carrier mobilities, all of which are essential for accurate performance prediction.

Fig. 2 Simulated PSC device structure using GPVDM (FTO/TiO_2/$CsPbI_3$/$ZnCo_2O_4$/Au).



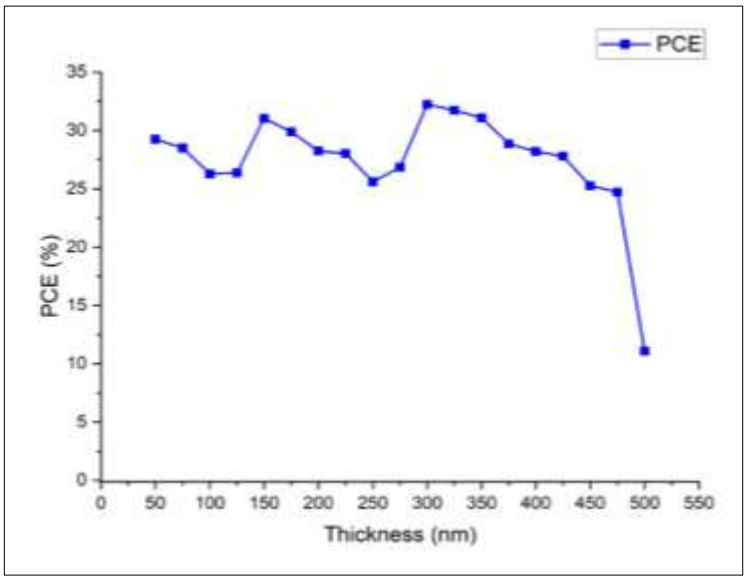
Result and Analysis

In this investigation, the thickness of the Zinc Cobaltite HTL is treated as a key design parameter in determining the optimum configuration for achieving maximum PCE in the PSC. To systematically evaluate its influence, multiple $ZnCo_2O_4$ thicknesses were simulated to identify the level that yields the highest device performance while maintaining stability and efficient charge extraction. The simulated HTL thicknesses ranged from 50 nm to 500 nm, with incremental steps of 25 nm (i.e., 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375, 400, 425, 450, 475, and 500 nm). Each configuration was analyzed under identical boundary conditions using the GPVDM simulation environment to ensure consistent comparison. After completing all simulations, the output parameters—including current density, open-circuit voltage, fill factor, and PCE—were collected, tabulated, and analyzed to determine the optimal $ZnCo_2O_4$ thickness for enhanced photovoltaic performance.

The design architecture and material composition of PSCs play a critical role in determining the optimal HTL thickness, which directly influences charge extraction efficiency and overall device performance. The HTL serves as a selective contact that facilitates efficient hole extraction from the perovskite absorber while blocking electrons, thereby minimizing interfacial recombination losses. An appropriately optimized HTL thickness ensures a balance between efficient charge transfer and minimal series resistance, leading to higher PCE [27], [28].

If the HTL is too thin, incomplete perovskite coverage or insufficient hole collection may occur, resulting in lower photocurrent and increased interfacial recombination [5]. Conversely, an excessively thick HTL can hinder carrier transport due to higher series resistance and limited conductivity, ultimately degrading fill factor and efficiency [29]. Previous studies indicate that the optimum HTL thickness for both organic and inorganic systems typically falls within the range of 50–300 nm, depending on the carrier mobility, energy-level alignment, and interface quality of the material [28], [29]. Therefore, systematic experimental or simulation-based optimization is essential to identify the ideal HTL thickness for a specific PSC configuration, accounting for variations in charge extraction, film conductivity, and contact resistance [30].

Fig. 3 Variation of PCE over thickness



As illustrated in Fig. 3, the PCE of the PSC exhibits a non-linear dependence on the thickness of the $ZnCo_2O_4$ HTL. The simulation was conducted while maintaining constant thicknesses for the ETL equal to 200 nm of TiO_2 and the perovskite absorber layer around 400 nm of $CsPbI_3$. The HTL thickness was varied from 100 nm to 500 nm to evaluate its impact on device performance.

According to Fig. 3, the PCE initially increases with HTL thickness due to improved hole extraction and reduced interfacial recombination. The maximum PCE was achieved at an optimal HTL thickness of approximately 300 nm, beyond which efficiency begins to saturate and eventually decline as the film becomes excessively thick. When the $ZnCo_2O_4$ layer exceeded 400 nm, charge transport was impeded due to increased series resistance and limited carrier mobility, resulting in reduced photocurrent and fill factor. Conversely, a too-thin HTL (< 150 nm) may lead to incomplete coverage, inefficient hole injection from the perovskite absorber into the HTL, and poor interfacial charge balance—ultimately diminishing device performance. These findings align with earlier reports that highlight the crucial role of optimized HTL thickness in achieving balanced charge transport and minimizing recombination losses in PSCs [5], [8], [28], [29].

Taguchi method result

Following the completion of the thickness optimization study, the Taguchi method was employed as a secondary optimization approach to identify the key factors that significantly influence the PCE of the PSC. The Taguchi method is a robust statistical design of experiments (DOE) technique that enables systematic evaluation of multiple parameters while minimizing the number of simulations or experiments required [8], [31]. In this study, three control factors were selected: (1) the thickness of the $ZnCo_2O_4$ HTL, (2) the operating temperature, and (3) the bandgap energy of $ZnCo_2O_4$.

An L9 (3^3) orthogonal array was employed to organize the experimental simulations efficiently. This design allows the investigation of three factors, each at three different levels, across only nine simulation runs instead of 27 (as required in a full factorial design). Each simulation output was analyzed using the S/N ratio, a key statistical indicator used to evaluate the robustness of the system. In this context, the “larger-the-better” criterion was applied to maximize PCE while minimizing variations caused by noise factors [32].

After evaluating the results, the main effects plot and response table were generated to determine which parameter exerted the greatest influence on device performance. The analysis revealed that bandgap energy and HTL thickness had the strongest effects on PCE, followed by temperature, consistent with previous research that employed Taguchi optimization for photovoltaic devices [8], [33]. This approach provided a clear understanding of parameter interactions, enabling the identification of an optimal $ZnCo_2O_4$ HTL thickness of 300 nm, a bandgap of 2.0 eV, and an operating temperature of 300 K for achieving the highest simulated PCE.

Table III Perovskite solar cell efficiency, PCE result by using Taguchi method.

PCE, %	1	2	3	4	5	6	7	8	9
1	26.2461	25.1502	20.3966	28.0222	26.7720	25.6031	32.1788	30.8296	29.4924
2	26.2463	25.1504	20.6049	28.0227	26.7739	25.6036	32.1798	30.8304	29.4932
3	26.2465	25.1506	20.7637	28.0231	26.7756	25.6040	32.1807	30.8310	29.4939
4	26.2461	25.1502	20.3966	28.0222	26.7720	25.6031	32.1788	30.8296	29.4924
5	26.2463	25.1504	20.6049	28.0227	26.7739	25.6036	32.1798	30.8304	29.4932
6	26.2465	25.1505	20.7637	28.0231	26.7756	25.6039	32.1807	30.8310	29.4939
7	26.2461	25.1502	20.3966	28.0222	26.7720	25.6031	32.1788	30.8296	29.4924
8	26.2463	25.1504	20.6049	28.0227	26.7739	25.6036	32.1798	30.8304	29.4932
9	26.2465	25.1505	20.7637	28.0231	26.7756	25.6038	32.1807	30.8310	29.4939

Table IV Fill factor, FF result by using Taguchi method.

FF, %	1	2	3	4	5	6	7	8	9
1	71.5	84.1	71.8	71.5	83.7	84.4	68.5	82.7	84.1
2	71.5	84.1	72.5	71.5	83.7	84.4	68.5	82.7	84.1
3	71.5	84.1	73.1	71.5	83.7	84.4	68.5	82.7	84.1
4	71.5	84.1	71.8	71.5	83.7	84.4	68.5	82.7	84.1
5	71.5	84.1	72.5	71.5	83.7	84.4	68.5	82.7	84.1
6	71.5	84.1	73.1	71.5	83.7	84.4	68.5	82.7	84.1
7	71.5	84.1	71.8	71.5	83.7	84.4	68.5	82.7	84.1
8	71.5	84.1	72.5	71.5	83.7	84.4	68.5	82.7	84.1
9	71.5	84.1	73.1	71.5	83.7	84.4	68.5	82.7	84.1

Table V Open circuit voltage, Voc result by using Taguchi method.

Voc	1	2	3	4	5	6	7	8	9
1	1.372753	1.372834	1.3729	1.37275	1.372831	1.372897	1.372747	1.372828	1.372893
2	1.119604	1.119613	1.11962	1.119604	1.119613	1.11962	1.119604	1.119613	1.11962
3	1.062949	1.062872	1.062809	1.062949	1.062872	1.062809	1.062949	1.062872	1.062809
4	1.370915	1.371109	1.371266	1.370915	1.371109	1.371266	1.370915	1.371109	1.371266
5	1.119132	1.119201	1.119256	1.119132	1.119201	1.119256	1.119132	1.119201	1.119256
6	1.061612	1.061611	1.06161	1.061611	1.061610	1.061601	1.061611	1.061610	1.061609
7	1.425072	1.425646	1.426111	1.425072	1.425646	1.426111	1.425072	1.425646	1.426111
8	1.132573	1.132622	1.132662	1.132572	1.132622	1.132662	1.132572	1.132622	1.132662
9	1.065460	1.065456	1.065453	1.065460	1.065456	1.065453	1.065460	1.065456	1.065453

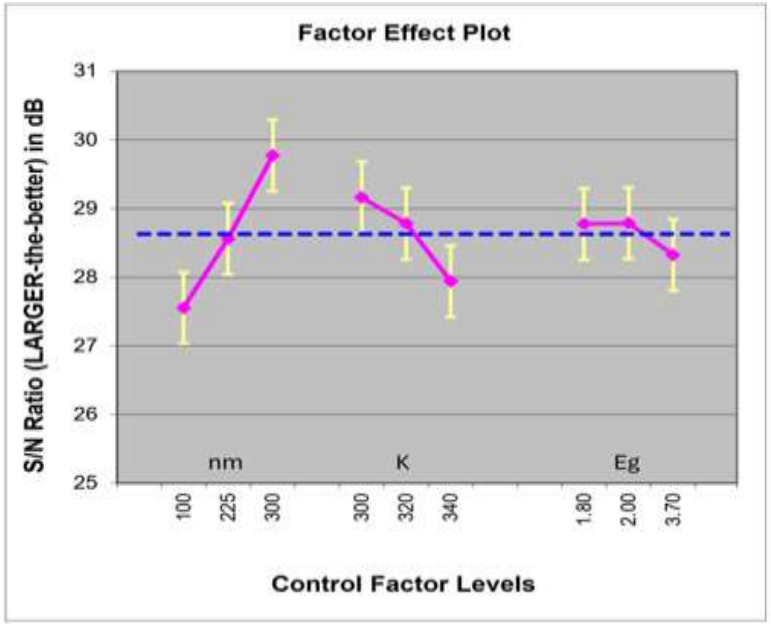
Table VI Current density, Jsc result by using Taguchi method.

Jsc	1	2	3	4	5	6	7	8	9
1	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.922	-32.883	-32.886
2	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.921	-32.883	-32.886
3	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.921	-32.883	-32.886
4	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.921	-32.883	-32.886
5	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.921	-32.883	-32.886
6	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.921	-32.883	-32.886
7	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.921	-32.883	-32.886
8	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.921	-32.883	-32.886
9	-26.707	-26.709	-26.721	-28.553	-28.580	-28.549	-32.921	-32.883	-32.886

Based on the analysis of Tables III to VI, which summarize the simulation results obtained using the Taguchi method, a clear variation in the PCE values can be observed across different parameter combinations. These results indicate that all investigated factors—the $ZnCo_2O_4$ HTL thickness, operating temperature, and bandgap energy—exert measurable influences on the PCE, even if their individual effects vary in magnitude. The observed pattern reveals that among these parameters, the HTL thickness has the most significant impact on device performance, confirming its critical role in determining efficient charge extraction, carrier mobility, and recombination suppression within the PSC structure.

This finding is consistent with previous optimization studies, which reported that fine-tuning the HTL thickness substantially affects the balance between series resistance and charge transport, thereby influencing both the fill factor and overall efficiency of the device [29], [32]. While temperature and bandgap energy also contribute to PCE variation, their effects are secondary compared to the dominant influence of the HTL thickness, as confirmed by the main effects plot and S/N ratio analysis derived from the Taguchi design [31].

Fig. 3 Factor effects plot of the S/N ratio for the "larger-the-better" criterion in Taguchi optimization, illustrating the influence of control factors on the PCE of the perovskite solar cell. The S/N ratio increases markedly with $ZnCo_2O_4$ HTL thickness up to 300 nm, followed by a gradual decline at higher values, indicating the existence of an optimal HTL thickness.



As shown in Fig. 3, the S/N ratio for the "larger-the-better" criterion demonstrates a strong correlation between the $ZnCo_2O_4$ HTL thickness and the PCE of the device. The ratio rises sharply from 100 nm to 300 nm, indicating significant improvements in charge extraction and reduced interfacial recombination at this range. Beyond 300 nm, a decline in S/N ratio is observed, suggesting that excessively thick HTLs introduce additional series resistance and impede hole transport, thereby reducing device efficiency. The maximum S/N ratio (~30 dB) recorded at 300 nm corresponds to the optimal thickness, at which the perovskite device achieves a stable and balanced carrier transport pathway. This trend aligns with previous studies reporting similar optimization behavior for inorganic HTLs, where moderate film thicknesses ensure complete coverage, adequate conductivity, and minimized recombination losses [5], [29], [32].

Table VII Result of ANOVA for PCE.

	PCE		
Factor	Thickness (nm)	Temperature (K)	Bandgap (Eg)
Degrees of Freedom	2	2	2
Sum of Squares	7	2	0
Mean Square	4	1	0
Factor Effect, %	70	22	4

The results of the ANOVA presented in Table VII indicate that the thickness of the $ZnCo_2O_4$ HTL exerts the most dominant influence on the PCE of the PSC. The factor contributes approximately 70 % of the total variance in PCE, followed by temperature (22 %) and bandgap energy (4 %). This outcome confirms that HTL thickness plays a pivotal role in determining charge-transport balance and minimizing recombination losses within the PSC structure. A variation in the HTL thickness directly alters the charge extraction pathway and the series resistance, leading to significant efficiency changes.

Table VIII Best setting selection for respective parameter.

Control factor parameter	Thickness (nm)	Temperature (K)	Bandgap (Eg)
Best level	3	1	2
Best value	300	300	2.0

The best parameter settings obtained through the Taguchi optimization are summarized in Table VIII. The optimal configuration corresponds to a $ZnCo_2O_4$ thickness of 300 nm (Level 3), ambient temperature of 300 K (Level 1), and bandgap of 2.0 eV (Level 2). These levels were selected based on the highest mean signal-to-noise ratios, confirming that this combination yields a robust and stable operating condition for the PSC under study.

Table IX Result after the confirmation experiment.

Experiment	PCE,%	FF, %	Voc	Jsc
1	32.2307	68.7	1.425845	-32.887
2	32.2314	68.7	1.426271	-32.886
3	32.232	68.7	1.426615	-32.886
4	32.2307	68.7	1.425845	-32.887
5	32.2314	68.7	1.426271	-32.886
6	32.232	68.7	1.426615	-32.886

7	32.2307	68.7	1.425845	-32.887
8	32.2314	68.7	1.426271	-32.886
9	32.232	68.7	1.426615	-32.886

A confirmation experiment was subsequently conducted using the optimized parameter set, and the results are shown in Table IX. The observed PCE values ranged narrowly between 32.230 % and 32.232 %, indicating strong reproducibility and model reliability. The corresponding fill factor (FF) remained stable at approximately 68.7 %, while the open-circuit voltage (Voc) and short-circuit current density (Jsc) values were consistent at around 1.426 V and −32.89 mA/cm², respectively. The highest simulated efficiency of 32.232 % was obtained at Level 9, validating the accuracy of the Taguchi-based optimization.

The high consistency of results across all nine trials confirms that the selected control parameters yield an optimized and stable PSC configuration. This aligns with recent studies demonstrating that fine-tuning inorganic HTL parameters—particularly $ZnCo_2O_4$ thickness and bandgap—can markedly improve PCE and thermal stability compared with organic HTLs such as PEDOT:PSS or spiro-OMeTAD [5], [29], [32], [33]. Furthermore, incorporating noise factors (hole and electron mobilities at Level 3, 9.14×10^{-6} cm^2 V^{-1} s^{-1}) enhances the robustness of the model by accounting for potential material variability.

In summary, the Taguchi-based ANOVA and confirmation analysis conclusively establish that the $ZnCo_2O_4$ HTL thickness (300 nm), ambient temperature (300 K), and bandgap (2.0 eV) represent the optimal conditions for achieving maximum PCE (~32.23 %) in the simulated perovskite solar cell.

CONCLUSION

This study successfully demonstrated that $ZnCo_2O_4$ is a highly promising HTL material for PSCs, offering superior stability, durability, and PCE compared with conventional organic HTLs. Using GPVDM simulation and Taguchi statistical optimization, the device achieved an optimal PCE of 32.23% at a $ZnCo_2O_4$ thickness of 300 nm, temperature of 300 K, and bandgap of 2.0 eV. The ANOVA and S/N ratio analyses confirmed that HTL thickness exerts the strongest influence on PCE, followed by temperature and bandgap energy. These results validate $ZnCo_2O_4$ as a robust and efficient HTL capable of enhancing carrier extraction and minimizing recombination losses.

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