Jurnal Riset Kimia

ISSN (print) : 1978-628X
ISSN (online) : 2476-8960

Optimization of P3HT:PCBM Bulk Heterojunction Polymer Solar Cells: Effects of Annealing Temperature and Active Layer Composition

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Received: January 2025
Accepted: August 2025
Published: September 2025

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Abstract

P3HT:PCBM-based polymer solar cells have demonstrated potential as an affordable substitute for conventional silicon-based photovoltaics. The performance of P3HT:PCBM bulk heterojunction solar cells is examined in this work in relation to the annealing temperature and the composition of the active layer. The morphology of the active layer was characterized using SEM, while the electrical properties were measured using current-voltage (I-V) characterization. Our findings show that 150°C is the ideal annealing temperature, resulting in the maximum power conversion efficiency (PCE) of 2.58%. SEM analysis revealed that this temperature produces the most homogeneous surface morphology. Additionally, a P3HT:PCBM ratio of 3:1 resulted in the best device performance, with a PCE of 4.36%. Short-circuit current and open-circuit voltage increase when the blend's P3HT level increases. These results offer important information for optimizing the production of P3HT:PCBM-based polymer solar cells, which could lead to increased organic photovoltaic device efficiency and possible commercial outcomes.

Keywords: *Polymer Solar Cell; P3HT: PCBM; Annealing; Active Layer Ratio; Bulk Heterojunction.*

Introduction

Energy sources can be classified as either renewable or non-renewable. Although there are renewable alternatives, non-renewable fossil fuels are still the main source of energy used worldwide [1–5]. Because fossil fuel supplies are running low and an energy crisis is soon to come, this reliance is alarming. In Indonesia, projections indicate a significant shortfall between fuel supply and demand, highlighting the urgent need for sustainable energy solutions [6–9]. Solar energy has emerged as a promising renewable option [10–16]. Solar cells, capable of harnessing sunlight for both household and industrial use, offer a decent solution to meet energy needs [15–20]. While silicon-based solar cells dominate the market, environmental concerns have encouraged the development of eco-friendly alternatives like Graetzel cells or Dye-Sensitized Solar Cells (DSSC) [21–28]. DSSC technology offers benefits in terms of reduced production costs and easier manufacturing procedures, despite currently being less efficient than silicon-based cells. This is a promising step towards more affordable and sustainable solar energy options [6,9,25–27,29–31].

Third-generation photovoltaic cells, particularly polymer solar cells, are potentially the subject of renewable energy research aimed at improving their efficiency [32–37]. By using conjugated bond

DOI: https://doi.org/10.25077/jrk.v16i2.817

Intrinsically Conducting Polymers (ICPs), these cells can capture sunlight and transform it into electrical energy [38,39].

As time goes on, PSC has emerged as a promising candidate for next-generation photovoltaic devices due to its flexibility, low-cost fabrication, and manufacturing potential. Recent advancements have pushed PSC efficiency above 20% [40,41], particularly with non-fullerene acceptors and advanced polymer donors [42,43]. However, fullerene-based systems remain relevant in fundamental studies and low-cost applications due to their known energy levels, processing simplicity, and historical data[44].

Previous studies have explored the effects of solvent additives, layer thickness, and post-treatment methods, but fewer studies have provided correlations between annealing temperature, mixture composition, and their impact on device morphology and performance, especially using readily accessible fabrication conditions [45–48]. This study addresses this gap by examining the influence of annealing temperature and precursor ratio on surface morphology and photovoltaic performance, aiming to provide a reproducible and cost-effective optimization route.

This study employs P3HT (poly 3-hexylthiophene) and PCBM (phenyl-C61-butyric acid methyl ester) polymers as the active layer in solar cell preparation (Figure 1). P3HT, a polythiophene subtype, serves as an electron donor and p-type semiconductor, valued for its Regular Region (RR) structure and ease of processing [49,50]. It can be formed into thin films using various simple techniques [51,52]. P3HT is a p-type semiconductor polymer because it has a conjugated π backbone. When exposed to light, electrons are excited from the HOMO level to the LUMO, leaving holes in the HOMO [53,54]. These holes act as majority carriers, enabling charge transport [55]. This hole-dominated conduction that determines its p-type semiconductor behavior.

PCBM functions as an electron acceptor and n-type semiconductor, with energy levels complementary to P3HT [56]. When P3HT absorbs light and an electron is excited to its LUMO, the electron is energetically favorable to transfer to the LUMO of PCBM [57]. This efficient electron transfer results in charge separation, with electrons moving through PCBM and holes remaining in P3HT, enabling current generation in the device [58,59]. The combination of P3HT and PCBM significantly enhances the performance of polymer solar cells, making it a promising candidate for efficient organic photovoltaics [60].

Despite their current poor efficiency, polymer-based solar cells provide tremendous possibilities for inexpensive, readily manufactured renewable energy solutions [35,61,62]. This study focused on improving their performance by focusing on controlling the active layer morphology through annealing treatments and active layer ratios.

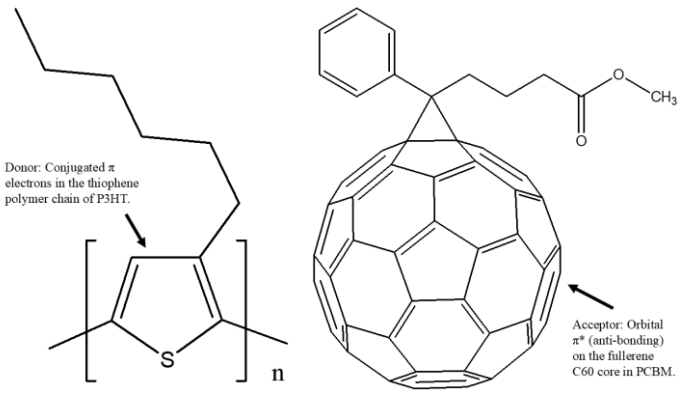

Figure 1. Structure of P3HT (left) and PCBM (right) polymer

While previous studies have optimized either annealing or P3HT:PCBM ratio individually, few have explored their combined effects. Annealing improves crystallinity and charge transport [63,64], while composition strongly affects efficiency [65,66]. This study addresses that gap by jointly optimizing both parameters under low-cost conditions to enhance morphology and device performance.

A range of annealing temperatures was investigated; 120°C was selected to surpass the glass transition temperature of P3HT, while 180°C was set to prevent it from melting [67]. We also investigated three different ratios of P3HT:PCBM, 1:1, 2:1, and 3:1, with an emphasis on increasing P3HT proportion due to its high conductivity and role as a key active ingredient [68]. Because there are more electron-hole pairs available for current generation at higher P3HT concentrations, improved light-to-electricity conversion efficiency is expected. The study aimed to maximize the active layer's morphology and, in turn, raise the efficiency of polymer-based solar cells by optimizing these variables.

Experimental

Material and Method

The materials used include Transparent Conductive Oxide (TCO) ITO, polymers (P3HT and PCBM), PEDOT:PSS, chlorobenzene, methanol, graphite and distilled water. First, the ITO substrate is washed thoroughly using soap water, methanol, and distilled water, followed by drying and masking [68]. PEDOT:PSS is prepared by dissolving 0.05 gram in 1.5 mL distilled water to form a paste. The active layer is created by mixing P3HT and PCBM in chlorobenzene at various ratios, 1:1, 2:1, 3:1, with each component dissolved separately before combining. A graphite counter electrode is prepared by coating it onto the ITO substrate (by heating the glass over a fire source (candle) until a carbon layer forms on the glass) and heating to ensure good contact. This study blends P3HT and PCBM polymers in an emulsion form using the bulk heterojunction approach, which has benefits over conventional bilayer structures like increased charge carrier mobility, innovative cell configurations, and better light absorption efficiency (Figure 2) [69,70]. The bulk heterojunction layer functions as the anode, although with lower performance than ITO (Indium Tin Oxide), while the counter electrode serves as the cathode [71]. Utilizing the distinct qualities of both P3HT and PCBM in a single-blended active layer, this arrangement seeks to maximize the polymer-based solar cell's overall performance.

Assembly begins with coating PEDOT:PSS paste onto the ITO layer, followed by baking it at 120°C for 60 minutes. The P3HT:PCBM active layer is then applied using spin coating at 600 rpm for 30 seconds. This layer goes through annealing at temperatures ranging from 120°C, 135°C, 150°C, 165°C, and 180°C for 10 minutes [67]. The carbon counter electrode is placed on top of the active layer (Figure 3).

The material used as the DSSC substrate is Indium Tin Oxide (ITO) glass. The ITO glass is cut into 1.25 cm x 1.25 cm pieces. The edges of the ITO glass are smoothed using a cotton bud. The layer is formed into 1 cm x 1 cm pieces.

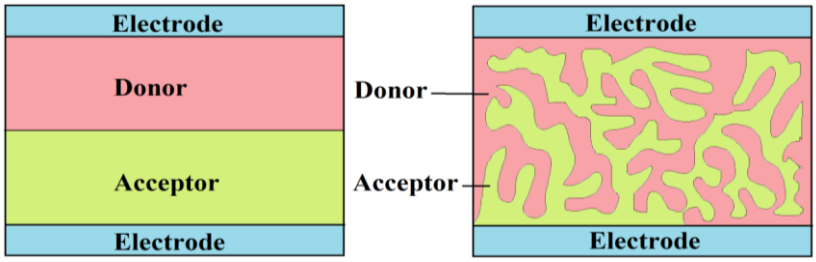

Figure 2. The difference of structure between bilayer (left) and bulk (right) heterojunction

DOI: https://doi.org/10.25077/jrk.v16i2.817

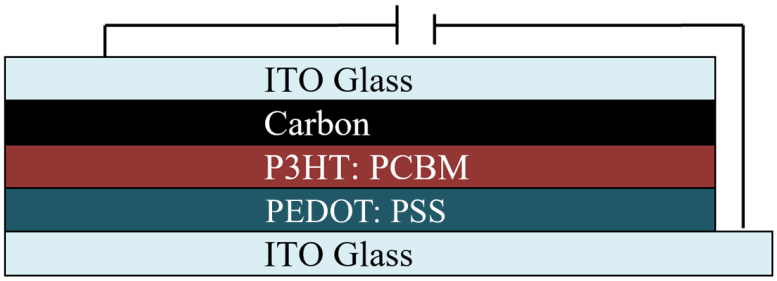

Figure 1. Solar cell structure with an active layer of a mixture of P3HT and PCBM

The characterization and performance evaluation of the polymer solar cells involves two approaches. First, Scanning Electron Microscopy (SEM) was used to analyze the morphology of the active layer to provides insights into the structure of the P3HT:PCBM thin film. Next, the efficiency is determined through measurements of voltage and resistance using a digital multimeter under a 30 W UV lamp. The P3HT: PCBM film exhibits strong absorbance in the 350–600 nm range, which overlaps with the emission spectrum of the 30W UV lamp used (~365–400 nm) [72–74]. This indicates the compatibility between the light source and the optical response of the active layer.

The efficiency (η) is calculated using equation 1 where P_{max} is the maximum power output, P_{in} is the input power, V_{max} is the maximum voltage, I_{max} is the current, I_{Light} is the light intensity, and L is the illuminated area. The light intensity and active area were measured to estimate input power.

$$\eta = \frac{P_{max}}{P_{in}} x\ 100\% = = \frac{V_{max}\ x\ I_{max}}{I_{light}\ x\ L} x\ 100\% \quad 1$$

All measurements for each experimental condition were conducted in duplicate (n = 2) to ensure reproducibility. Voltage and current values were recorded manually under UV illumination, and the resulting efficiency was calculated from the average of two repeated trials.

Results and Discussion

The active layer consisting of P3HT:PCBM generates electrical potential due to the semiconducting characteristics of this polymer. The conjugated bonds in its structure allow the generation of electrons upon exposure to UV light, with charge carriers moving from cathode to anode via intermolecular forces within the active layer. The ITO substrate undergoes a lithography process to ensure cleanliness and facilitate the deposition of the coating. The PEDOT:PSS solution appeared as a dark blue paste, while the P3HT:PCBM mixture formed a red-brown paste.

PEDOT:PSS was applied to the ITO substrate and heated to 120°C to remove excess moisture and improve adhesion. After deposition via a rotary coating, the P3HT:PCBM layer undergoes heating to optimize its morphology. For solar cell characterization, a 30 W UV lamp was used instead of direct sunlight to ensure consistent test conditions, as the intensity of natural sunlight can vary. This approach allows for more accurate and reproducible efficiency measurements. Binder clips secured both sides of the device during testing to maintain its structural integrity.

The structure of P3HT:PCBM-based organic solar cells consists of several main layers (Figure 4). The bottom layer is transparent ITO-coated glass that functions as an anode or hole collector. Above it is the PEDOT:PSS layer, which functions as the hole transport layer, responsible for transporting holes to the ITO electrode. The active layer consists of a mixture of P3HT and PCBM, where P3HT acts as an electron donor through the conjugated π electrons in its polymer chain, while PCBM functions as an electron acceptor, receiving electrons in the π^* orbital of its C60 fullerene core. This active layer is where light absorption, exciton formation

(electron-hole pairs), and charge separation occur. Above the active layer is typically a carbon electrode layer (or other material) that acts as the cathode or electron collector. Our scheme uses an ITO layer on top as well, although typically only one ITO layer is used at the bottom as the anode.

In its physical operation, incoming light is absorbed by the P3HT:PCBM active layer, forming excitons. These excitons then dissociate at the interface between the donor (P3HT) and acceptor (PCBM) into electrons and holes. Electrons move toward the PCBM and flow to the carbon electrode (cathode), while holes move in the opposite direction through the PEDOT:PSS layer toward the ITO electrode (anode). The flow of electrons and holes forms the electric current in the solar cell.

The electric properties of polymer solar cells at different annealing temperatures

The effect of annealing temperature on the performance of these solar cells was investigated. To determine the optimal annealing temperature, we experimented with temperatures of 120°C, 135°C, 150°C, 165°C, and 180°C. At these various heating temperatures, the output voltage of polymer solar cells with a P3HT:PCBM ratio of 1:1 was measured. UV light intensity of 30W/m^2 was used to directly assess the cell's capacity to convert it into electricity. The results showed that the prepared polymer solar cells successfully converted light energy into electrification.

The results, as shown in Figure 5, revealed that the voltage increased from 1.085V at 120°C to 1.121V at 135°C. A significant jump in voltage was observed at 150°C, reaching the highest value of 4.029V. However, a slight decrease to 4.023V occurred at 165°C, followed by a substantial drop to 1.164V at 180°C. The electric current generated by the polymer solar cells was also measured. Additionally, the efficiency and annealing temperature trend are correlated in a manner like that of the voltage and electric current data, with the best efficiency recorded at 150°C. The efficiency values were 0.23% at 120°C, 0.48% at 135°C, and peaked at 2.58% at 150°C. Above 150°C, the efficiency decreases, reaching 1.72% at 165°C and only 0.5% at 180°C. Error bars in Figures 5 and 6 represent the standard deviation from duplicate measurements. While the number of repetitions was limited to two due to material constraints, consistent trends were observed across all samples, supporting the reliability of the findings.

The results showed a continuous increase in performance from 120°C to 150°C. This improvement is attributed to the mixing of P3HT and PCBM polymers at the glass transition temperature of 110°C, which produces more regular fabric crystals and higher hole mobility. During the annealing process, P3HT restructures itself, allowing P3HT and PCBM molecules to move freely within the thin film.

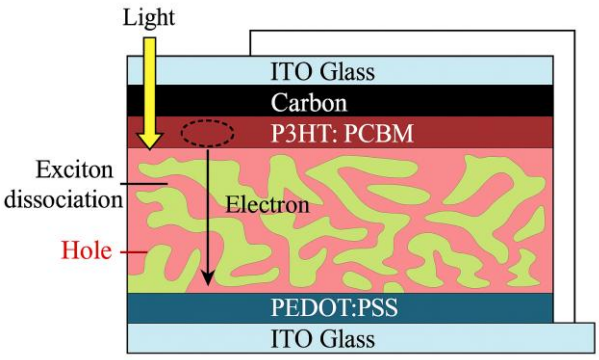

Figure 4. Voltage, current power, and efficiency curves as functions of annealing temperature

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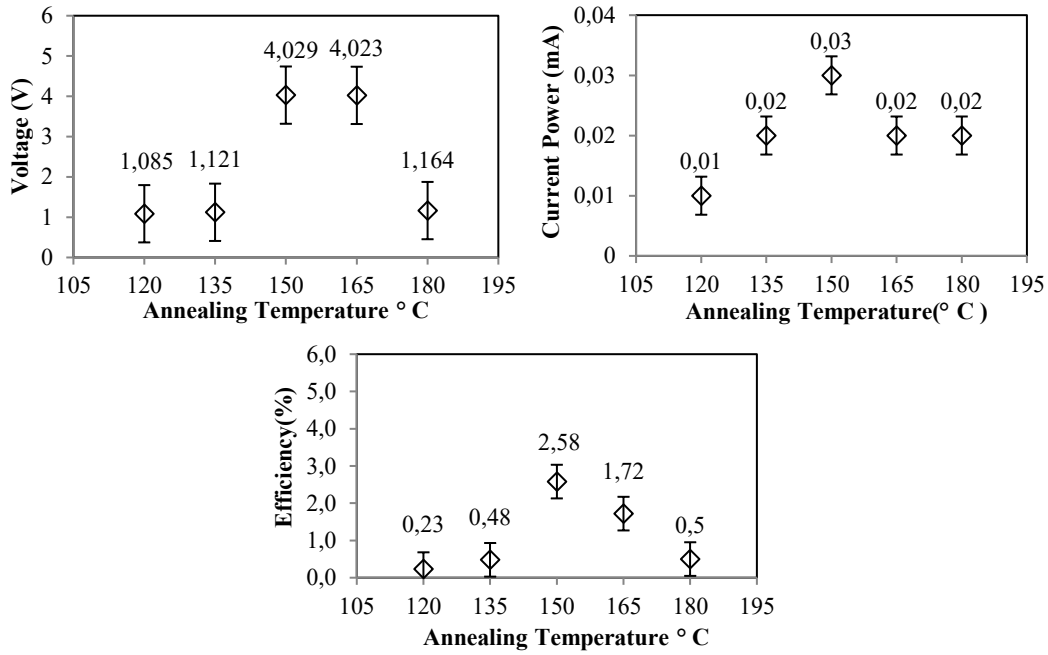

Figure 5. Voltage, current power, and efficiency curves as functions of annealing temperature

On the other hand, a drop in performance (at 165°C and 180°C) has been demonstrated that raising the annealing temperature can result in color changes, which indicate that the polymer active layer has reached its melting point. Based on these findings, the study concluded that the optimum condition for increasing solar cell efficiency is morphology control at an annealing temperature of 150°C. This finding provides a foundation for future research aimed at optimizing the ratio of P3HT:PCBM in polymer solar cells to further improve their performance and efficiency.

The efficiency of polymer solar cells is highly dependent on the uniformity of the active layer. We improve it by applying an annealing process, which helps restore the uniformity of P3HT polymer and crystallite structure, which may have been disrupted by the presence of PCBM polymer. Thermal treatment of solar cells can also enhance charge carrier mobility, improve interlayer transport, and promote interfacial uniformity. P3HT:PCBM active layers were deposited on PEDOT:PSS-coated ITO glass substrates. The samples were subjected to various heating temperatures and then analyzed using Scanning Electron Microscopy (SEM) at 40,000 times magnification. Based on previous studies that showed peak efficiency, heating temperatures of 135°C, 150°C, and 165°C were investigated.

SEM characterization showed a marked difference in surface morphology among the samples (Figure 6). The samples annealed at 150°C showed a more uniform and smoother surface than those treated at 135°C or 165°C. The improved uniformity at 150°C can be attributed to the increased crystallinity and phase separation between the P3HT and PCBM components. This optimized morphology likely facilitates more efficient exciton dissociation and charge transport in the active layer. The smoother surface may also result in better contact with the next electrode layer, potentially reducing the interfacial resistance. At lower temperatures (135°C), insufficient thermal energy can result in incomplete reorganization of polymer chains and fullerene molecules. Conversely, excessive temperatures (165°C) may cause overgrowth of PCBM domains or disruption of the optimal P3HT crystal structure. These morphological changes at non-optimal temperatures can negatively impact device performance by creating charge traps or reducing the effective interface area between donor and acceptor components.

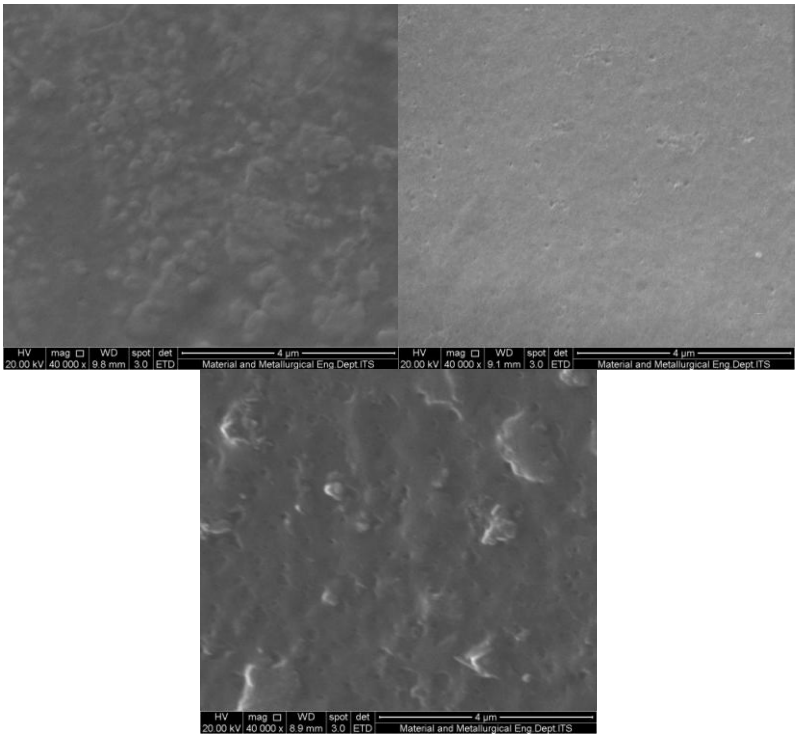

Figure 6. SEM result of P3HT: PCBM active layer with annealing 135°C (left), 150°C (middle), and 165°C (right)

Further analysis shows that the sample annealed at 150°C has only small pits on its surface, indicating a well-precipitated polymer layer with reactive crystallinity. This improved morphology is due to the restructuring of P3HT at this temperature. The presence of small pits may be due to areas not completely covered by the deposited polymer during the rotary coating process and the annealing process is expected to correct this. However, the active layers annealed at 135°C and 165°C show fewer flat surfaces with some accumulations. Samples annealed at 135°C also showed more accumulated areas compared to those annealed at 165°C, which highlights the significant impact of temperature variation on the morphological homogeneity of the active layer.

The electrical properties of polymer solar cells with different active layer ratios

This study investigated the effects of varying the polymer mixing ratio in solar cells, specifically focusing on increasing the proportion of P3HT relative to PCBM. P3HT, known for its high conductivity, serves as both an electron donor and photon absorber in polymer solar cells. The ratios of P3HT:PCBM examined were 1:1, 2:1, and 3:1, with the hypothesis that increasing the P3HT content would lead to greater photon absorption and electron release, potentially improving solar cell efficiency.

The first electric property tested was the voltage generated by solar cells with different active ingredient ratios. As illustrated in Figure 7, increasing the P3HT ratio results in higher voltage output. Solar cells with a 1:1 P3HT:PCBM ratio produced 4.029 V, while those with a 2:1 ratio generated 4.043 V, showing a modest increase of 0.014 V. The highest voltage of 4.089 V was achieved with the 3:1 P3HT: PCBM ratio, demonstrating that a higher proportion of P3HT in the mixture can indeed boost voltage output.

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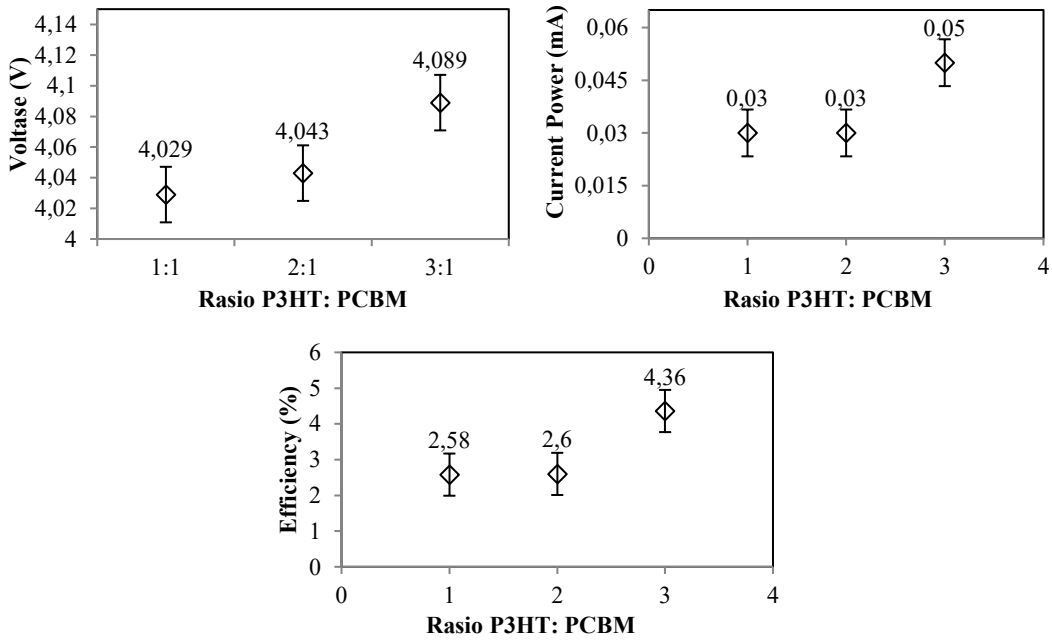

Figure 7. Voltage, current power, and efficiency as functions of the polymer active layer ratio

The study also examined the power produced by each solar cell configuration. Remarkably, solar cells with 1:1 and 2:1 P3HT:PCBM ratios both produced 0.03 mA, while the 3:1 ratio cell showed an increase to 0.05 mA. This suggests that the 3:1 ratio is most effective in converting light into electrical current, likely due to the increased number of electrons and holes generated by the higher P3HT content.

Efficiency calculations based on these results revealed that solar cells with 1:1 and 2:1 P3HT:PCBM ratios achieved efficiencies of 2.58% and 2.6% respectively, showing only a marginal difference. However, the 3:1 ratio cell demonstrated a significant improvement, reaching an efficiency of 4.36%. Figure 6 illustrates this relationship between efficiency and concentration ratio.

While higher P3HT ratios allow for increased light absorption and exciton production, it is important to note that not all generated electrons successfully reach the cathode due to recombination (75–78). Conversely, when PCBM composition is higher, light absorption and exciton production decrease, resulting in fewer free charges available for transfer to the cathode.

Several factors can impact solar cell efficiency beyond the P3HT:PCBM ratio. Residual solution and steam on the active layer after the spin coating process can lead to holes and morphological distortions when annealed (79,80). Oxygen exposure can also affect performance by binding to carbon atoms in the polymer double chain, disrupting P3HT conjugated molecules (81,82). Additionally, limited photon energy resources directly influence solar cell performance (79,81). This study shows that increasing the P3HT:PCBM ratio to 3:1 will greatly boost polymer solar cells' efficiency, however several factors need to be considered to maximize performance.

Conclusions

The research demonstrates that annealing temperature plays a crucial role in device efficiency, with 150°C emerging as the optimal temperature, resulting in a peak efficiency of 2.58%. This temperature produces the most homogeneous and flat surface morphology of the active layer, which is critical for efficient charge transport. Furthermore, the study reveals that increasing the P3HT content in the active layer significantly enhances device

performance. A P3HT:PCBM ratio of 3:1 achieved the highest efficiency of 4.36%, attributed to improved light absorption and charge generation. These findings highlight the balance required in the active layer composition, where sufficient P3HT is needed for light absorption and exciton generation, while maintaining adequate PCBM for efficient charge separation. These results provide valuable guidance for future development of polymer solar cells, suggesting that improving both the annealing process and active layer composition can lead to significant improvements in organic photovoltaic technology

Acknowledgments

We would like to express our sincerest gratitude to all those who have assisted with the implementation of this research project, with particular thanks going to LPPM Uniska MAB for their generous support.

Declaration of Generative AI and AI-Assisted Technologies

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Author Contributions

H.: Methodology, investigation, data collection, formal analysis, data curation, visualization, writing —original draft preparation. H.S.: Methodology, investigation, data collection. R.I.N.H.: Methodology, validation, supervision, and writing —review and editing. P.P.: Conceptualization, supervision, corresponding author responsibilities.

Funding

Funding information is not available.

Declaration of Conflicting Interests

The authors declare no conflict of interest.

References

1. Hartono D, Hastuti SH, Halimatussadiah A, Saraswati A, Mita AF, Indriani V. Comparing the impacts of fossil and renewable energy investments in Indonesia: A simple general equilibrium analysis. Heliyon. 2020 Jun;6(6):e04120.
2. Achakulwisut P, Erickson P, Guivarch C, Schaeffer R, Brutschin E, Pye S. Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions. Nat Commun. 2023 Sep 13;14(1):5425.
3. Holechek JL, Geli HME, Sawalhah MN, Valdez R. A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050? Sustainability. 2022 Apr 16;14(8):4792.
4. Singh S, Bansal P, Bhardwaj N. A Study on Nexus Between Renewable Energy and Fossil Fuel Consumption in Commercial Sectors of United States Using Wavelet Coherence and Quantile-on-Quantile Regression. Front Energy Res. 2022 Mar 8;10.
5. Adewunmi Adelekan O, Segun Ilugbusi B, Adisa O, Chimezie Obi O, Feranmi Awonuga K, Franca Asuzu O, et al. ENERGY TRANSITION POLICIES: A GLOBAL REVIEW OF SHIFTS TOWARDS RENEWABLE SOURCES. Engineering Science & Technology Journal [Internet]. 2024;5(2):272–87. Available from: www.fepbl.com/index.php/estj
6. Pambudi NA, Firdaus RA, Rizkiana R, Ulfa DK, Salsabila MS, Suharno, et al. Renewable Energy in Indonesia: Current Status, Potential, and Future Development. Sustainability. 2023 Jan 27;15(3):2342.
7. Resosudarmo BP, Rezki JF, Effendi Y. Prospects of Energy Transition in Indonesia. Bull Indones Econ Stud. 2023 May 4;59(2):149–77.
8. Sujai M, Wahyudi R, Sakina NA. Transition from Coals to Renewable Energy: Evidence from Indonesia. 2023 Oct.
9. Sistriatmaja MB, Samudro BR, Pratama YP, Prasetyo A. Energy transition as a way to improve the welfare of Indonesian society. Multidisciplinary Reviews. 2024 Aug 10;7(12):2024283.
10. Sovacool BK. National context drives concerns. Nat Energy. 2018 Sep 10;3(10):820–

 DOI: https://doi.org/10.25077/jrk.v16i2.817

1.

11. Schiermeier Q, Tollefson J, Scully T, Witze A, Morton O. Energy alternatives: Electricity without carbon. Nature. 2008 Aug 13;454(7206):816–23.
12. Nijsse FJMM, Mercure JF, Ameli N, Larosa F, Kothari S, Rickman J, et al. The momentum of the solar energy transition. Nat Commun. 2023 Oct 17;14(1):6542.
13. Sharma L, Singh J, Dhiman R, Vargas Nunez DR, Ba AE, Joshi KJ, et al. Advancing Solar Energy for Primary Healthcare in Developing Nations: Addressing Current Challenges and Enabling Progress Through UNICEF and Collaborative Partnerships. Cureus. 2024 Jan 3;
14. Lv Y. Transitioning to sustainable energy: opportunities, challenges, and the potential of blockchain technology. Front Energy Res. 2023 Sep 14;11.
15. Maka AOM, Alabid JM. Solar energy technology and its roles in sustainable development. Clean Energy. 2022 Jun 1;6(3):476–83.
16. Soomar AM, Hakeem A, Messaoudi M, Musznicki P, Iqbal A, Czapp S. Solar Photovoltaic Energy Optimization and Challenges. Front Energy Res. 2022 May 30;10.
17. Gong J, Sumathy K, Qiao Q, Zhou Z. Review on dye-sensitized solar cells (DSSCs): Advanced techniques and research trends. Renewable and Sustainable Energy Reviews. 2017 Feb;68:234–46.
18. Devadiga D, Selvakumar M, Shetty P, Santosh MS. Recent progress in dye sensitized solar cell materials and photo-supercapacitors: A review. J Power Sources. 2021 May;493:229698.
19. Machín A, Márquez F. Advancements in Photovoltaic Cell Materials: Silicon, Organic, and Perovskite Solar Cells. Materials. 2024 Mar 1;17(5):1165.
20. Hasan MM, Hossain S, Mofijur M, Kabir Z, Badruddin IA, Yunus Khan TM, et al. Harnessing Solar Power: A Review of Photovoltaic Innovations, Solar Thermal Systems, and the Dawn of Energy Storage Solutions. Energies (Basel). 2023 Sep 6;16(18):6456.
21. Singh R. Why silicon is and will remain the dominant photovoltaic material. J Nanophotonics. 2009 Jul 1;3(1):032503.
22. M. Lunardi M, Alvarez-Gaitan JP, Chang NL, Corkish R. Life cycle assessment on PERC solar modules. Solar Energy Materials and Solar Cells. 2018 Dec;187:154–9.
23. Hardeli, Hijri F, Sanjaya H, Putri YP, Permatasari P. THE EFFECT OF COATING IN INCREASING THE EFFICIENCY OF SOLAR CELLS BY USING QUERCETIN POLY AS A DYE. Rasayan Journal of Chemistry. 2023 Jul 1;16(3):1925–31.
24. Hardeli, Sanjaya H, Permatasari P, Novita IP, Agdisti NF, Luli R, et al. TiO2-Ag AND NATURAL DYE CO-PIGMENTED WITH SALICYLIC ACID FOR DYE-SENSITIZED SOLAR CELL (DSSC) APPLICATION. Rasayan Journal of Chemistry. 2022 Jan 1;15(1):569–78.
25. Machín A, Márquez F. Advancements in Photovoltaic Cell Materials: Silicon, Organic, and Perovskite Solar Cells. Materials. 2024 Mar 1;17(5):1165.
26. Dhorkule M, Lamrood P, Ralegankar S, Patole SP, Wagh SS, Pathan HM. Unveiling the Efficiency of Dye-Sensitized Solar Cells: A Journey from Synthetic to Natural Dyes. ES Food & Agroforestry. 2024;
27. Tamilselvan SN, Shanmugan S. Towards sustainable solar cells: unveiling the latest developments in bio-nano materials for enhanced DSSC efficiency. Clean Energy. 2024 Jun 1;8(3):238–57.
28. Spinelli G, Freitag M, Benesperi I. What is necessary to fill the technological gap to design sustainable dye-sensitized solar cells? Sustain Energy Fuels. 2023;7(4):916–27.
29. Razykov TM, Ferekides CS, Morel D, Stefanakos E, Ullal HS, Upadhyaya HM. Solar photovoltaic electricity: Current status and future prospects. Solar Energy. 2011 Aug;85(8):1580–608.
30. O'Regan B, Grätzel M. A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films. Nature. 1991

Oct;353(6346):737–40.

31. Nazeeruddin MdK, Baranoff E, Grätzel M. Dye-sensitized solar cells: A brief overview. Solar Energy. 2011 Jun;85(6):1172–8.
32. Freitag M, Daniel Q, Pazoki M, Sveinbjörnsson K, Zhang J, Sun L, et al. High-efficiency dye-sensitized solar cells with molecular copper phenanthroline as solid hole conductor. Energy Environ Sci. 2015;8(9):2634–7.
33. Cichosz S, Masek A, Zaborski M. Polymer-based sensors: A review. Polym Test. 2018 May;67:342–8.
34. Hardeli, Sanjaya H, Permatasari P, Karnila R. Improvement of Solar Cell Performance by Annealing Temperature Treatment and Active Layer Ratio. Vol. 41, J. Chem. Chem. Eng. Research Article. 2022.
35. Zhang L, Yao Z, Wang H, Zhang J, Ma X, Zhang F. Recent Progress of All Polymer Solar Cells with Efficiency Over 15%. Solar RRL. 2023 Jun 3;7(12).
36. Lee JW, Park JS, Jeon H, Lee S, Jeong D, Lee C, et al. Recent progress and prospects of dimer and multimer acceptors for efficient and stable polymer solar cells. Chem Soc Rev. 2024;53(9):4674–706.
37. Fu J, Fong PWK, Liu H, Huang CS, Lu X, Lu S, et al. 19.31% binary organic solar cell and low non-radiative recombination enabled by non-monotonic intermediate state transition. Nat Commun. 2023 Mar 30;14(1):1760.
38. Inzelt G. Conducting Polymers. Berlin, Heidelberg: Springer Berlin Heidelberg; 2012.
39. Xue Q, Hu Z, Liu J, Lin J, Sun C, Chen Z, et al. Highly efficient fullerene/perovskite planar heterojunction solar cells via cathode modification with an amino-functionalized polymer interlayer. J Mater Chem A. 2014;2(46):19598–603.
40. Ren X, Jung HS. Recent Progress in Flexible Perovskite Solar Cell Development. Journal of the Korean Ceramic Society. 2018 Jul 31;55(4):325–36.
41. Ma Y, Lu Z, Su X, Zou G, Zhao Q. Recent Progress Toward Commercialization of Flexible Perovskite Solar Cells: From Materials and Structures to Mechanical Stabilities. Advanced Energy and Sustainability Research. 2023 Jan 23;4(1).
42. Wang S, Gong XY, Li MX, Li MH, Hu JS. Polymers for Perovskite Solar Cells. JACS Au. 2024 Sep 23;4(9):3400–12.
43. Zhao C, Wang J, Jiao J, Huang L, Tang J. Recent advances of polymer acceptors for high-performance organic solar cells. J Mater Chem C Mater. 2020;8(1):28–43.
44. Lin HS, Matsuo Y. Fullerenes in Photovoltaics. In: Handbook of Fullerene Science and Technology. Singapore: Springer Nature Singapore; 2022. p. 851–88.
45. Guo X, Zhang M, Ma W, Zhang S, Hou J, Li Y. Effect of solvent additive on active layer morphologies and photovoltaic performance of polymer solar cells based on PBDTTT-C-T/PC71BM. RSC Adv. 2016;6(57):51924–31.
46. Rosa ES, Shobih S. Effectiveness of annealing treatment and polymer blends on i-v characteristsics of polymer solar cell. Reaktor. 2014 Dec 9;14(4):261.
47. Oyewole DO, Oyewole OK, Kushnir K, Shi T, Oyelade O V., Adeniji SA, et al. Pressure and thermal annealing effects on the photoconversion efficiency of polymer solar cells. AIP Adv. 2021 Apr 1;11(4).
48. Zhao G, He Y, Peng B, Li Y. Effect of Device Fabrication Conditions on Photovoltaic Performance of Polymer Solar Cells Based on Poly(3-hexylthiophene) and Indene-C 70 Bisadduct. Chin J Chem. 2012 Jan 16;30(1):19–22.
49. Marrocchi A, Lanari D, Facchetti A, Vaccaro L. Poly(3-hexylthiophene): synthetic methodologies and properties in bulk heterojunction solar cells. Energy Environ Sci. 2012;5(9):8457.
50. von Hauff E, Parisi J, Dyakonov V. Investigations of the effects of tempering and composition dependence on charge carrier field effect mobilities in polymer and fullerene films and blends. J Appl Phys. 2006 Aug 15;100(4).
51. Ebadian S, Gholamkhass B, Shambayati S, Holdcroft S, Servati P. Effects of annealing and degradation on regioregular

 DOI: https://doi.org/10.25077/jrk.v16i2.817

polythiophene-based bulk heterojunction organic photovoltaic devices. Solar Energy Materials and Solar Cells. 2010 Dec;94(12):2258–64.

52. Tremel K, Ludwigs S. Morphology of P3HT in Thin Films in Relation to Optical and Electrical Properties. In 2014. p. 39–82.
53. B. Suleiman A, Maigari A, S. Gidado A, E. Ndikilar C. Density Functional Theory Study of the Structural, Electronic, Non-Linear Optical and Thermodynamic Properties of Poly (3-Hexylthiophene-2, 5 - Diyl) in Gas Phase and in Some Solvents. Physical Science International Journal. 2022 Aug 27;34–51.
54. Crossland EJW, Tremel K, Fischer F, Rahimi K, Reiter G, Steiner U, et al. Anisotropic Charge Transport in Spherulitic Poly(3-hexylthiophene) Films. Advanced Materials. 2012 Feb 7;24(6):839–44.
55. Tanabe I, Tanaka Y. Attenuated Total Reflectance UV-Vis Spectroscopy Applied for Organic Semiconductor Films. ECS Meeting Abstracts. 2024 Nov 22;MA2024-02(59):3958–3958.
56. Zhang F, Zhuo Z, Zhang J, Wang X, Xu X, Wang Z, et al. Influence of PC60BM or PC70BM as electron acceptor on the performance of polymer solar cells. Solar Energy Materials and Solar Cells. 2012 Feb;97:71–7.
57. D'Avino G, Mothy S, Muccioli L, Zannoni C, Wang L, Cornil J, et al. Energetics of Electron–Hole Separation at P3HT/PCBM Heterojunctions. The Journal of Physical Chemistry C. 2013 Jun 27;117(25):12981–90.
58. Chen M, Hou J, Hong Z, Yang G, Sista S, Chen L, et al. Efficient Polymer Solar Cells with Thin Active Layers Based on Alternating Polyfluorene Copolymer/Fullerene Bulk Heterojunctions. Advanced Materials. 2009 Nov 13;21(42):4238–42.
59. Chang SC, Hsiao YJ, Li TS. P3HT:PCBM Incorporated with Silicon Nanoparticles as Photoactive Layer in Efficient Organic Photovoltaic Devices. J Nanomater. 2013 Jan 14;2013(1).
60. Aernouts T, Vanlaeke P, Poortmans J, Heremans P. Polymer solar cells: screen-printing as a novel deposition technique. MRS Proceedings. 2004 Feb 1;836:L3.9.
61. Ahmed A, Elsakka M, Elminshawy N, Mohamed A, Sundaram S. Recent Advances in Floating Photovoltaic Systems. The Chemical Record. 2023 Dec 12;23(12).
62. Gorjian S, Sharon H, Ebadi H, Kant K, Scavo FB, Tina GM. Recent technical advancements, economics and environmental impacts of floating photovoltaic solar energy conversion systems. J Clean Prod. 2021 Jan;278:124285.
63. Cheng CE, Dinelli F, Yu CT, Shih HW, Pei Z, Chang CS, et al. Influences of thermal annealing on P3HT/PCBM interfacial properties and charge dynamics in polymer solar cells. Jpn J Appl Phys. 2015 Dec 1;54(12):122301.
64. Motaung DE, Malgas GF, Nkosi SS, Mhlongo GH, Mwakikunga BW, Malwela T, et al. Comparative study: the effect of annealing conditions on the properties of P3HT:PCBM blends. J Mater Sci. 2013 Feb 13;48(4):1763–78.
65. Siddiqui H, Parra MR, Pandey P, Qureshi MS, Haque FZ. Combined parametric optimization of P3HT: PC70BM films for efficient bulk-heterojunction solar cells. Journal of Solid State Electrochemistry. 2019 Dec 9;23(12):3267–74.
66. Yamanari T, Taima T, Hara K, Saito K. Investigation of optimum conditions for high-efficiency organic thin-film solar cells based on polymer blends. J Photochem Photobiol A Chem. 2006 Sep;182(3):269–72.
67. Lu Y, Wang Y, Feng Z, Ning Y, Liu X, Lü Y, et al. Temperature-dependent morphology evolution of P3HT:PCBM blend solar cells during annealing processes. Synth Met. 2012 Dec;162(23):2039–46.
68. Berger PR, Kim M. Polymer solar cells: P3HT:PCBM and beyond. Journal of Renewable and Sustainable Energy. 2018 Jan 1;10(1).
69. Dahou FZ, Cattin L, Garnier J, Ouerfelli J, Morsli M, Louarn G, et al. Influence of anode roughness and buffer layer nature on organic solar cells performance. Thin Solid Films.

2010 Aug;518(21):6117–22.

70. Günes S, Neugebauer H, Sariciftci NS. Conjugated Polymer-Based Organic Solar Cells. Chem Rev. 2007 Apr 1;107(4):1324–38.
71. Jørgensen M, Norrman K, Krebs FC. Stability/degradation of polymer solar cells. Solar Energy Materials and Solar Cells. 2008 Jul;92(7):686–714.
72. Prasad SS, Divya G, Kumar KS. P3HT Thin Films And Their Optical Characterization. In: 2021 2nd International Conference on Advances in Computing, Communication, Embedded and Secure Systems (ACCESS). IEEE; 2021. p. 5–8.
73. Naik I, Bhajantri R, Naik L, Patil BS, Pragasam U shetti, Rathod S, et al. Optically tuned poly (3-hexylthiophene-2,5-diyl) P3HT/PCBM (modified fullerene) blend for plastic solar cell. Nanosystems: Physics, Chemistry, Mathematics. 2016 Aug 24;691–4.
74. Maruhashi H, Oku T, Suzuki A, Akiyama T, Yamasaki Y. Fabrication and Characterization of PCBM: P3HT-based Thin-film Organic Solar Cells with Zinc Phthalocyanine and 1,8-Diiodooctane. Chemical and Materials Engineering. 2017 Jan;5(1):1–7.
75. Li Y, Huang B, Zhang X, Ding J, Zhang Y, Xiao L, et al. Lifetime over 10000 hours for organic solar cells with Ir/IrOx electron-transporting layer. Nat Commun. 2023 Mar 4;14(1):1241.
76. Al-Mousoi AK, Mohammed MKA, Kumar A, Pandey R, Madan J, Dastan D, et al. Understanding Auger recombination in perovskite solar cells. Physical Chemistry Chemical Physics. 2023;25(24):16459–68.
77. He C, Chen Z, Wang T, Shen Z, Li Y, Zhou J, et al. Asymmetric electron acceptor enables highly luminescent organic solar cells with certified efficiency over 18%. Nat Commun. 2022 May 11;13(1):2598.
78. Younsi Z, Meddour F, Bencherif H, Hossain MK, Marasamy L, Sasikumar P, et al. Scrutinizing transport phenomena and recombination mechanisms in thin film Sb2S3 solar cells. Sci Rep. 2024 May 30;14(1):12460.
79. Zhou Y, Najar A, Zhang J, Feng J, Cao Y, Li Z, et al. Effect of Solvent Residue in the Thin-Film Fabrication on Perovskite Solar Cell Performance. ACS Appl Mater Interfaces. 2022 Jun 29;14(25):28729–37.
80. Dailey M, Li Y, Printz AD. Residual Film Stresses in Perovskite Solar Cells: Origins, Effects, and Mitigation Strategies. ACS Omega. 2021 Nov 16;6(45):30214–23.
81. Fernandes M, Wrasse EO, Kawata Koyama CJ, Günther FS, Coutinho DJ. Unrevealing the interaction between O2 molecules and poly(3-hexylthiophene-2,5-diyl) (P3HT). RSC Adv. 2022;12(29):18578–84.
82. Mkawi EM, Al-Hadeethi Y, Bazuhair RS, Yousef AS, Shalaan E, Arkook B, et al. Optimization of Sb2S3 Nanocrystal Concentrations in P3HT: PCBM Layers to Improve the Performance of Polymer Solar Cells. Polymers (Basel). 2021 Jun 29;13(13):2152.

 DOI: https://doi.org/10.25077/jrk.v16i2.817