

Impact of Urban Air Pollution and Climatic Factors on Photovoltaic Performance: A Comparative Modelling Study Across Major Indian Cities

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Abstract: Solar photovoltaic (PV) systems play an important role in India's transition towards renewable energy. However, their performance can be significantly influenced by environmental conditions that vary across different urban regions. This study investigates the impact of urban pollution and climatic conditions on photovoltaic efficiency in four Indian cities: Delhi, Mumbai, Jaipur, and Bangalore. The research sought to answer three primary questions: (1) How do climatic variables such as temperature, humidity, solar irradiation, sunshine hours, and cell temperature affect PV efficiency? (2) How does urban air pollution, represented by PM_{2.5} concentrations, influence photovoltaic performance? (3) How do these relationships differ across cities with varying climatic and pollution conditions? To address these questions, I collected monthly environmental and photovoltaic data and analysed them for each city over a one-year period. The study examined average temperature, PM_{2.5} concentration, solar irradiation, humidity, sunshine hours, cell temperature, and photovoltaic efficiency. A comparative modelling approach was used to evaluate both baseline PV efficiency and pollution-adjusted PV efficiency, while graphical and comparative analyses were performed to identify relationships between environmental variables and solar panel performance. The results showed that baseline PV efficiency remained relatively stable between 17.52% and 17.85%, whereas pollution-adjusted efficiency varied from 13.37% to 17.34%. Delhi experienced the highest PM_{2.5} concentration (237.4 µg/m³) and the greatest reduction in pollution-adjusted efficiency (13.37%), while Bangalore consistently recorded the highest overall performance, achieving a maximum pollution-adjusted efficiency of 17.34% due to its lower pollution levels and moderate climate. The study concludes that urban air pollution has a greater impact on effective photovoltaic performance than temperature or humidity alone, although all environmental variables contribute to variations in efficiency. These findings highlight the importance of incorporating local pollution and climatic conditions into photovoltaic system planning, enabling more accurate energy predictions and supporting the efficient deployment of solar energy systems in rapidly urbanising regions of India.

Keywords: Photovoltaic Efficiency, Urban Air Pollution (PM_{2.5}), Solar Irradiation, Climatic Factor

1. Introduction

The global transition towards renewable energy has accelerated in response to climate change, rising energy demand, and the depletion of fossil fuel resources. Among renewable sources, solar energy has emerged as one of the most promising due to its abundance, sustainability, and declining cost of technology. India, in particular, has significant solar potential, receiving high solar irradiance for nearly 300 days a year. Through initiatives such as the Jawaharlal Nehru National Solar Mission, India aims to generate large-scale electricity from solar photovoltaic (PV) systems to enhance energy security and reduce greenhouse gas emissions (S. Ghosh et al., 2023; S. Ghosh et al., 2024). However, despite this potential, real-world PV performance often falls short of expected values due to environmental and urban factors, making it crucial to understand these influences in detail.

Photovoltaic systems generate electricity by converting sunlight into electrical energy through the photoelectric effect. The efficiency of this process depends on several environmental and operational variables. Solar irradiance is the primary factor, as higher sunlight intensity increases energy output. However, temperature has an inverse effect, with higher temperatures reducing PV efficiency by increasing the operating temperature of the cells and lowering their electrical output (Prasanthi, 2025; Baghel & Chander, 2022). In addition, atmospheric conditions such as humidity, cloud cover, and wind influence the amount of sunlight reaching the panel surface (A. Ghosh, 2020). Urban pollution also plays a significant role by scattering and absorbing

sunlight in the atmosphere, reducing the solar irradiance available for electricity generation (S. Ghosh et al., 2022; Bergin et al., 2017). These combined effects make PV performance highly sensitive to local climatic and environmental conditions.

Existing literature strongly highlights the negative impact of pollution and climate on photovoltaic efficiency. Studies conducted in India and globally show that dust accumulation can reduce PV output by up to 20–25%, and in extreme cases even higher (A. Ghosh, 2020; Chawla et al.). Research has demonstrated that particulate pollution reduces solar radiation reaching panels, leading to energy losses of approximately 17–25% in highly polluted regions (S. Ghosh et al., 2022; Bergin et al., 2017). Experimental studies in Indian cities have also shown that increased temperatures and dust deposition significantly reduce efficiency, while cleaning panels can restore performance (Prasanthi, 2025; Chawla et al.). Additionally, modelling studies using satellite and atmospheric data confirm that aerosols are a dominant factor in reducing solar irradiance, especially in urban and industrial regions such as the Indo-Gangetic Plain (S. Ghosh et al., 2023; Sethi & Kosmopoulos, 2025). These findings clearly establish that environmental factors are critical in determining real-world solar performance.

Although these studies have established the importance of individual environmental factors, they also reveal several limitations in the existing literature. Most studies focus on individual locations or specific variables, such as temperature or dust, rather than analysing multiple factors simultaneously. There is limited comparative research across different Indian

cities that experience varying levels of pollution and climatic conditions (Sethi & Kosmopoulos, 2025). Furthermore, few studies integrate both experimental measurements and modelling approaches to provide a comprehensive understanding of PV performance. The combined impact of urban pollution and climatic variability on photovoltaic efficiency across multiple regions remains insufficiently explored.

Therefore, this study aims to investigate the impact of urban pollution and climatic conditions on photovoltaic efficiency across selected Indian cities. It analyses key variables such as solar irradiance, temperature, particulate pollution, and humidity, and evaluates their combined effects on PV performance. By integrating experimental observations with modelling techniques, this research seeks to provide a comparative understanding of how different urban environments influence solar energy output. The findings will contribute to improving the efficiency, planning, and deployment of photovoltaic systems in India's rapidly urbanising landscape.

2. Literature Review

The reviewed papers across these ten studies demonstrate that urban pollution and climatic conditions have a significant influence on photovoltaic (PV) efficiency and solar energy generation in India. Together, the studies provide both experimental and modelling evidence showing that environmental factors such as temperature, solar irradiance, dust accumulation, humidity, particulate matter (PM_{2.5}), cloud cover, and aerosols directly affect the performance of photovoltaic systems (Prasanthi, 2025; Baghel & Chander, 2022; S. Ghosh et al., 2023; A. Ghosh, 2020). Since India is rapidly expanding its use of solar energy to meet increasing energy demands and climate goals, understanding these environmental impacts is essential for improving the reliability and efficiency of solar power systems, especially in highly urbanised and polluted regions (S. Ghosh et al., 2024).

One of the most commonly discussed variables across the reviewed papers is temperature. Nearly all studies concluded that while higher solar irradiance increases electricity generation, excessive temperature reduces the efficiency of photovoltaic cells (Prasanthi, 2025; Baghel & Chander, 2022). Experimental studies conducted in Southern India and Chhattisgarh found that as panel temperatures increased, PV efficiency declined noticeably. For example, Prasanthi (2025) observed that panel efficiency dropped from approximately 16% to 13.6% during hotter conditions, while Baghel and Chander (2022) reported that cooler months consistently produced better performance ratios compared to hotter periods. Rising temperatures increase the internal resistance of photovoltaic cells, which lowers voltage output and overall conversion efficiency (Baghel & Chander, 2022). Future climate modelling studies further predict that increasing temperatures due to climate change could reduce India's photovoltaic potential by 2–3% by mid-century, with additional days of overheating expected every year (S. Ghosh et al., 2024). These findings suggest that temperature is one of the most critical climatic variables affecting solar panel performance in India's warm environment.

Another major finding across the reviewed papers is the severe impact of urban pollution and dust accumulation on photovoltaic systems. Multiple studies identified particulate matter, aerosols, and dust deposition as the dominant causes of solar efficiency loss in Indian cities (S. Ghosh et al., 2023; A. Ghosh, 2020; Bergin et al., 2017). Air pollution reduces solar performance in two major ways. First, aerosols and suspended particles scatter and absorb incoming solar radiation in the atmosphere, reducing the amount of sunlight reaching the panels (S. Ghosh et al., 2022; Bergin et al., 2017). Second, deposited dust forms a physical layer on the panel surface, decreasing light transmittance and increasing panel heating (A. Ghosh, 2020; Chawla et al.). Studies by S. Ghosh and colleagues (2023) showed that air pollution can reduce India's solar energy potential by as much as 29%, particularly in highly polluted regions such as the Indo-Gangetic Plain. Experimental investigations by Bergin et al. (2017) and Chawla et al. demonstrated that dust accumulation can reduce photovoltaic efficiency by 20–50% depending on dust thickness, particle size, and environmental conditions. In some cases, cleaning solar panels increased power output by nearly 50%, highlighting the importance of regular maintenance in polluted urban environments (Bergin et al., 2017; Chawla et al.).

The reviewed studies also emphasised the importance of climatic variables such as humidity, rainfall, wind speed, and cloud cover in influencing photovoltaic efficiency (A. Ghosh, 2020). High humidity was found to increase the adhesion of dust particles to solar panel surfaces, making natural cleaning more difficult and worsening soiling losses (A. Ghosh, 2020). Monsoon conditions, especially in cities such as Mumbai and Pune, were associated with reduced solar irradiance due to dense cloud cover and lower sunlight duration (Baghel & Chander, 2022). However, rainfall and strong winds sometimes helped reduce dust accumulation by naturally cleaning the panels (A. Ghosh, 2020). Wind speed was generally observed to have a small positive effect because it helped cool the panels and reduce operating temperatures (Prasanthi, 2025). These findings demonstrate that photovoltaic performance is controlled not by a single environmental variable, but by the interaction of multiple climatic and pollution-related factors.

Several reviewed papers also compared photovoltaic performance across different Indian cities and regions. Urban areas with higher pollution concentrations and dense infrastructure were found to have lower solar potential compared to cleaner or less crowded regions (S. Ghosh et al., 2023; Sethi & Kosmopoulos, 2025). Research on rooftop photovoltaic systems showed that aerosols caused larger reductions in solar radiation than clouds in many Indian cities (Sethi & Kosmopoulos, 2025). Urban architecture, including tall buildings and shadowing effects, further reduced photovoltaic output by limiting sunlight exposure (Sethi & Kosmopoulos, 2025). Cities such as Delhi and Kanpur were repeatedly identified as regions experiencing significant solar losses because of severe pollution levels, while relatively cleaner cities showed better photovoltaic potential (S. Ghosh et al., 2022; Sethi & Kosmopoulos, 2025). These regional differences highlight the need for city-specific solar planning and environmental management strategies.

The methods used across the reviewed papers were highly diverse and included experimental monitoring, real-time rooftop PV testing, satellite observations, GIS mapping, atmospheric modelling, regression analysis, and climate projections (Prasanthi, 2025; Baghel & Chander, 2022; S. Ghosh et al., 2023; Patnaik et al., 2020). Several studies combined long-term satellite datasets such as MODIS and CERES with environmental models to evaluate solar radiation trends over many years (S. Ghosh et al., 2023; Sethi & Kosmopoulos, 2025). Others used controlled experimental chambers to study how greenhouse gas concentrations and dust deposition influence solar panel performance (Patnaik et al., 2020). Together, these approaches provide strong scientific evidence supporting the relationship between urban pollution, climatic conditions, and photovoltaic efficiency.

Overall, the reviewed papers strongly support the research topic, Impact of Urban Pollution and Climatic Conditions on Photovoltaic Efficiency: An Experimental and Modelling Study across Indian Cities. The studies consistently show that pollution, temperature, humidity, and climatic variability significantly reduce solar panel efficiency and energy production in India (Prasanthi, 2025; S. Ghosh et al., 2023; A. Ghosh, 2020). They also highlight that cleaner air, improved maintenance practices, and better urban planning could substantially improve photovoltaic performance and help India achieve its renewable energy goals (S. Ghosh et al., 2022; S. Ghosh et al., 2024).

3. Methodology

Research Design

This study employed a comparative observational and modelling-based research design to investigate the impact of urban pollution and climatic conditions on photovoltaic (PV) efficiency across different Indian cities. A comparative approach was selected because environmental conditions vary considerably between locations, allowing the influence of pollution and climate on PV performance to be evaluated under different real-world scenarios. By comparing multiple cities rather than focusing on a single location, it was possible to identify broader patterns and determine which environmental factors have the greatest influence on photovoltaic efficiency.

Study Locations

Four Indian cities were selected for the study: Delhi, Mumbai, Jaipur, and Bangalore. These cities were chosen because they represent distinct climatic zones and pollution profiles. Delhi was selected due to its consistently high levels of urban air pollution and large seasonal variations in temperature. Mumbai was chosen because of its coastal climate, high humidity levels, and relatively moderate pollution concentrations. Jaipur was included as an example of a hot and dry environment with high solar irradiance and relatively low humidity for much of the year. Bangalore was selected because it experiences moderate temperatures, lower pollution levels, and relatively stable climatic conditions throughout the year. Together, these cities provide a diverse range of environmental conditions suitable for comparative analysis.

Data Collection

Monthly data were collected for average temperature, PM_{2.5} concentration, solar irradiation, relative humidity, sunshine hours, and photovoltaic performance. The data were obtained from publicly available meteorological, solar resource, and air-quality databases. Monthly averages were used to reduce the influence of short-term fluctuations and provide a clearer representation of seasonal trends.

Data Processing

The collected data were organised into spreadsheets and grouped by city and month. Tables and graphs were produced to visualise seasonal changes in environmental conditions and photovoltaic performance. All variables were checked to ensure consistency in units and formatting before analysis.

Photovoltaic Performance Modelling

Temperature Correction

To evaluate the influence of environmental conditions on photovoltaic (PV) performance, a simplified modelling approach was adopted. Instead of directly measuring the output of a solar panel, standard photovoltaic performance equations were used to determine the effect of environmental factors on PV efficiency. This approach allowed the environmental data collected for each city to be converted into estimated PV performance values.

Solar panels generally operate at temperatures higher than the surrounding air because they absorb solar radiation. Therefore, the module temperature (Bamisile et al., 2025) was estimated using Equation (1).

$$T_{cell} = T_{air} + \frac{NOCT - 20}{800} E \quad (1)$$

Here, T_{cell} is the temperature of the solar cell, T_{air} is the temperature of the ambient, E is the solar irradiance in W/m^2 and NOCT is Nominal Operating Cell Temperature, which for commercial modules is 46.5°C.

The effect of temperature on photovoltaic efficiency was calculated using the standard temperature coefficient model (Skoplaki & Palyvos, 2009) given in Equation (2):

$$\eta = \eta_{ref} [1 - \beta_{ref} (T_{cell} - T_{air})] \quad (2)$$

Here, $\eta_{ref} = 18\%$ is the reference efficiency and $\beta_{ref} = 0.004/^{\circ}C$ is the Temperature coefficient. η is the efficiency of the module at an elevated temperature T_{cell} . This equation accounts for the decrease in solar panel efficiency as operating temperature increases.

Pollution Correction

Air pollution reduces the amount of sunlight reaching the surface of a solar panel because suspended particulate matter scatters and absorbs incoming solar radiation. Table 1 shows the amount of solar irradiation lost because of PM_{2.5} concentration (Dudáš et al., 2024). Higher PM_{2.5} concentrations results in lower effective solar irradiance available for electricity generation. This data was used to determine the loss in the module's efficiency because of PM_{2.5}.

Table 1: PM_{2.5} levels and their effect on the efficiency of solar cell.

Level off air pollution	PM2.5 (µg/m ³)	PM10 (µg/m ³)	Solar irradiation effect (average value)
Good	0-30	0-50	≈ 2.5% loss
Satisfactory	31-60	51-100	≈ 5% loss
Moderate	61-90	101-250	≈ 8% loss
Poor	91-120	251-350	≈ 12.5% loss
Very poor	121-250	351-430	≈ 25% loss
Severe	251+	431+	≈ 12.5% per each 100 µg/m ³

Modelling Approach

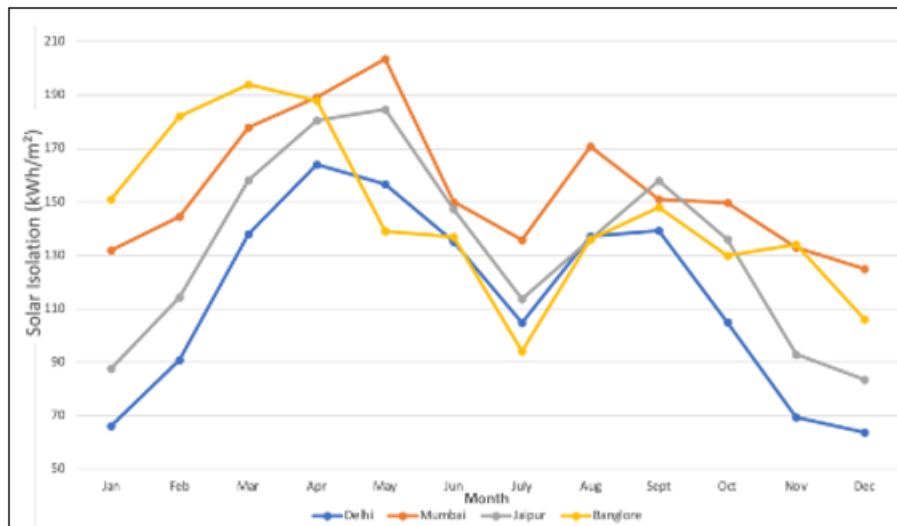
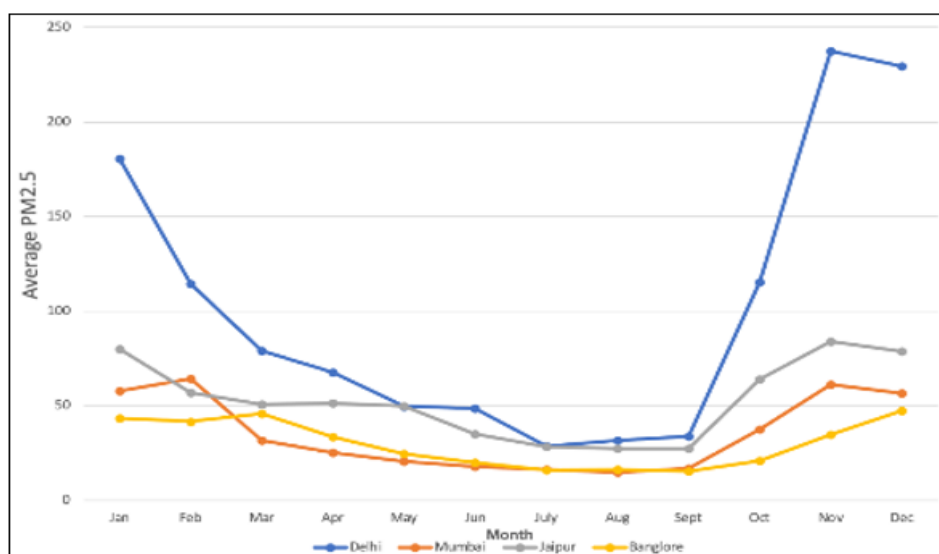
Photovoltaic cell temperature was estimated using the Nominal Operating Cell Temperature (NOCT) model, while PV efficiency was calculated using a standard temperature-coefficient relationship. The equations and modelling assumptions used in this study are shown in Figure 1. Pollution effects were incorporated using PM_{2.5} concentrations as an indicator of atmospheric aerosols, with irradiance losses estimated according to published PM_{2.5} categories. Humidity effects were incorporated qualitatively by considering their influence on atmospheric transparency, cloud formation, and dust adhesion on photovoltaic panels.

Comparative Analysis

The four cities were compared using monthly values of temperature, PM_{2.5} concentration, humidity, solar irradiation, sunshine hours, cell temperature, PV efficiency, and pollution-adjusted PV efficiency. Baseline and pollution-adjusted efficiencies were used to evaluate how climatic conditions and air pollution influenced photovoltaic performance across different urban environments.

Limitations

This study has several limitations. Monthly averages may not fully capture short-term variations in weather and pollution levels. Photovoltaic efficiency was estimated using literature-based models rather than direct measurements from operating solar installations. In addition, PM_{2.5} was used as the primary indicator of air pollution, while other pollutants were not considered. Finally, the study was limited to four cities and one year of data, which may not fully represent long-term environmental variability

4. Results and Discussion**Figure 1:** Month-wise average solar isolation of Delhi, Mumbai, Jaipur and Bangalore over the year**Figure 2:** Month-wise average PM2.5 isolation of Delhi, Mumbai, Jaipur and Bangalore over the year

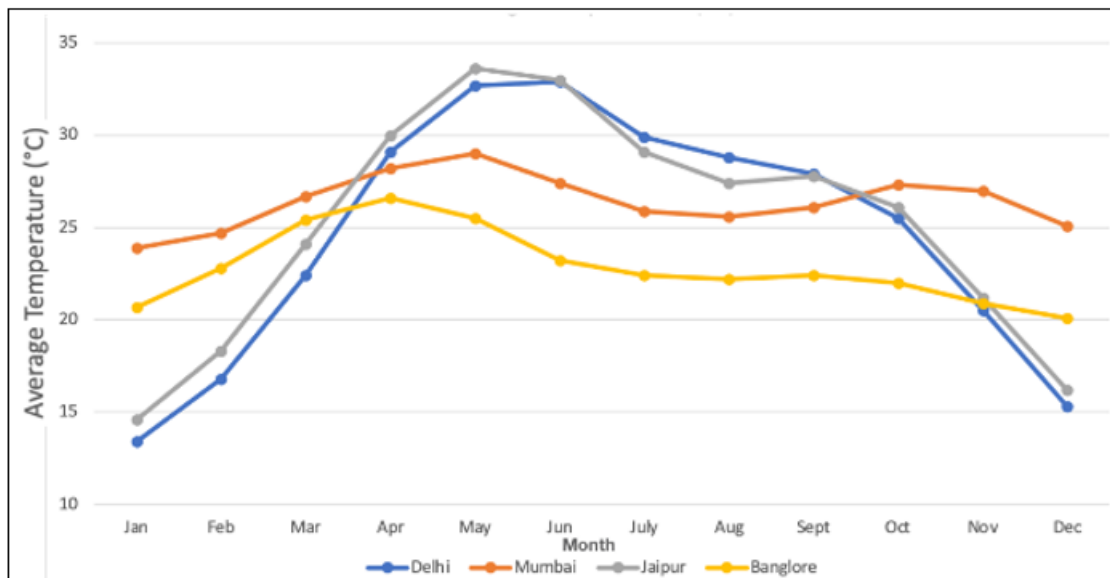


Figure 5: Month-wise average temperature of Delhi, Mumbai, Jaipur and Bangalore over the year

Climatic and Pollution Trends Across the Cities

The four cities exhibited distinct climatic and pollution conditions. As shown in Figure 2, Delhi recorded the highest PM_{2.5} concentrations, increasing from approximately 82 $\mu\text{g}/\text{m}^3$ in January to 237.4 $\mu\text{g}/\text{m}^3$ in November, while Figure 3 shows that it also experienced large seasonal temperature variations. Figure 6 indicates that Mumbai had relatively stable temperatures but the highest humidity levels, reaching 89% during July and August. Figure 4 shows that Jaipur

experienced the highest cell temperatures, reaching 39.7°C in May, alongside strong solar irradiation shown in Figure 1 and relatively low humidity shown in Figure 6. Figures 2, 3 and 4 demonstrate that Bangalore displayed the most moderate conditions, with the lowest PM_{2.5} concentrations (15.4–47.4 $\mu\text{g}/\text{m}^3$) and relatively stable temperatures throughout the year. These differences provided a suitable basis for evaluating how environmental conditions influence PV performance.

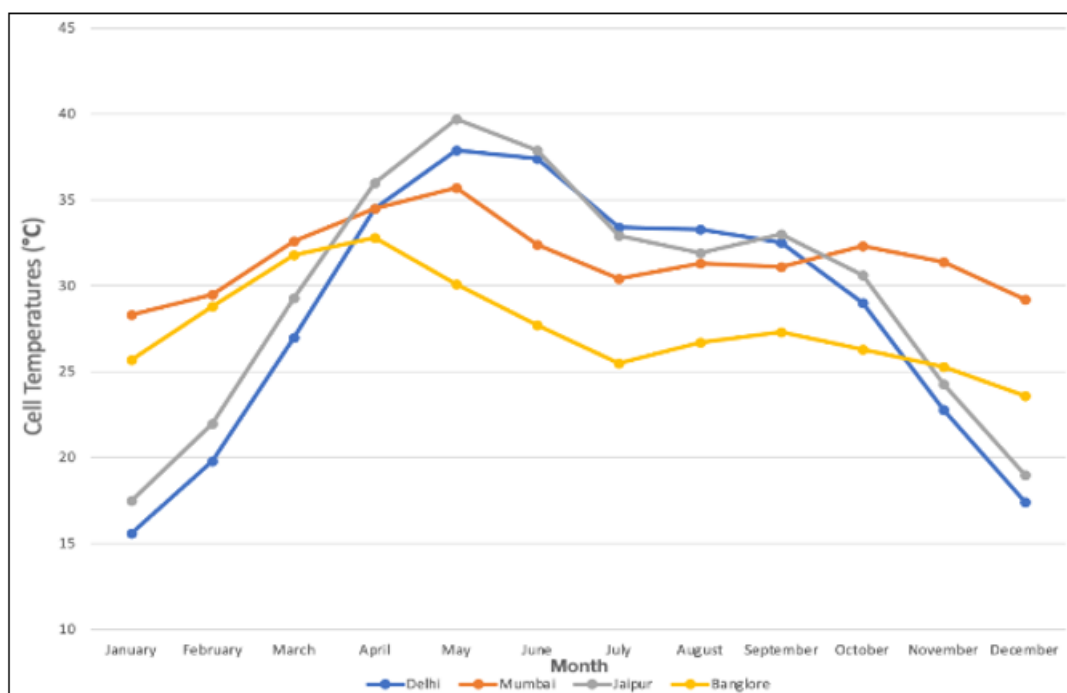


Figure 4: Month-wise average cell temperatures of Delhi, Mumbai, Jaipur and Bangalore over the year

Effect of Temperature on Photovoltaic Efficiency

Figure 4 shows that cell temperatures increased during the summer months in all four cities and were generally associated with lower PV efficiency. As observed from Figures 4 and 8, Delhi's cell temperature increased from 15.6°C in January to 34.5°C in April, while PV efficiency decreased from 17.84% to 17.61% over the same period. Similarly, Figures 4 and 8 show that Mumbai's cell

temperature rose from 28.3°C to 35.7°C between January and May, accompanied by a reduction in efficiency from 17.68% to 17.52%. Figure 4 also indicates that Jaipur recorded the highest cell temperature of 39.7°C in May, corresponding to reduced PV efficiency shown in Figure 8. These results indicate that increasing operating temperature reduces photovoltaic efficiency by lowering the open-circuit voltage of solar cells (Prasanthi, 2025; Baghel & Chander, 2022).

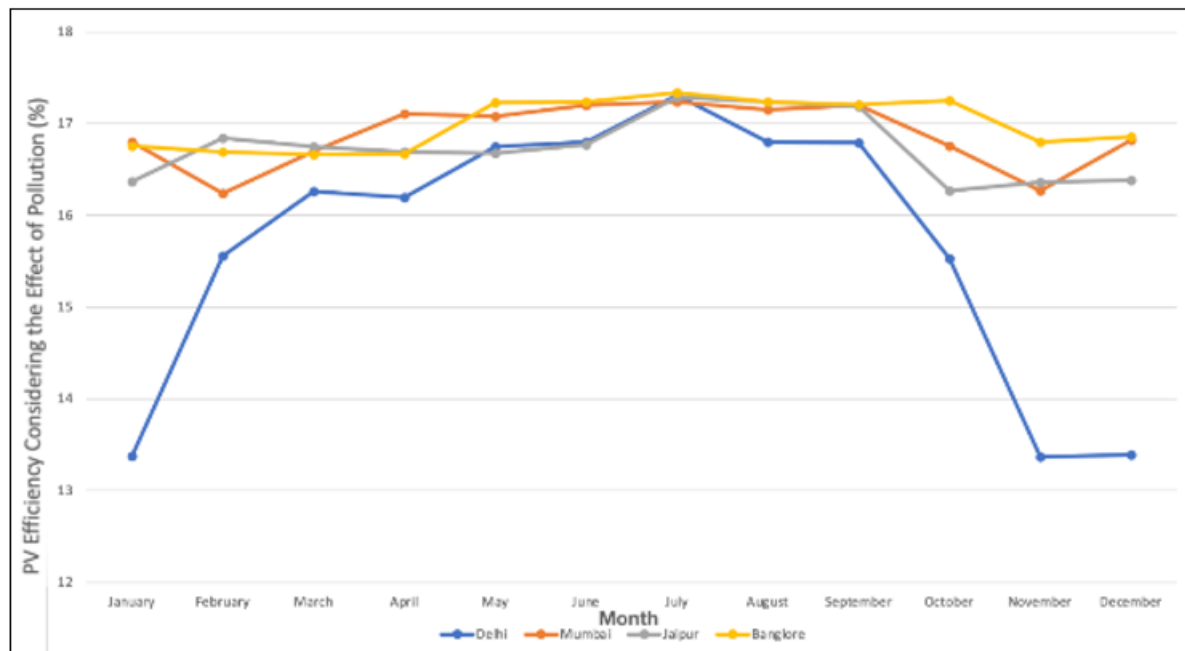


Figure 5: Month-wise PV Efficiency Considering the Effect of Pollution in Delhi, Mumbai, Jaipur and Bangalore over the year

Effect of Air Pollution on Photovoltaic Efficiency

Figure 3 shows that PM_{2.5} concentration had the strongest impact on photovoltaic performance. It can be observed from Figure 2 that Delhi experienced the highest pollution levels, reaching 237.4 $\mu\text{g}/\text{m}^3$ in November and 229.5 $\mu\text{g}/\text{m}^3$ in December. Correspondingly, Figure 5 shows that pollution-adjusted PV efficiency fell to 13.37% and 13.39%, despite baseline efficiencies remaining above 17.8% in Figure 8. Similarly, Figures 2 and 5 show that Jaipur's pollution-adjusted efficiency decreased to 16.36% when PM_{2.5}

concentrations increased to 84.1 $\mu\text{g}/\text{m}^3$. In contrast, Figure 2 indicates that Bangalore maintained PM_{2.5} concentrations below 50 $\mu\text{g}/\text{m}^3$ throughout the year, while Figure 5 shows only minor reductions in pollution-adjusted efficiency. These findings indicate that PM_{2.5} was the dominant environmental factor affecting PV performance, as airborne particles scatter and absorb incoming solar radiation before it reaches photovoltaic modules (S. Ghosh et al., 2022; S. Ghosh et al., 2023; Bergin et al., 2017).

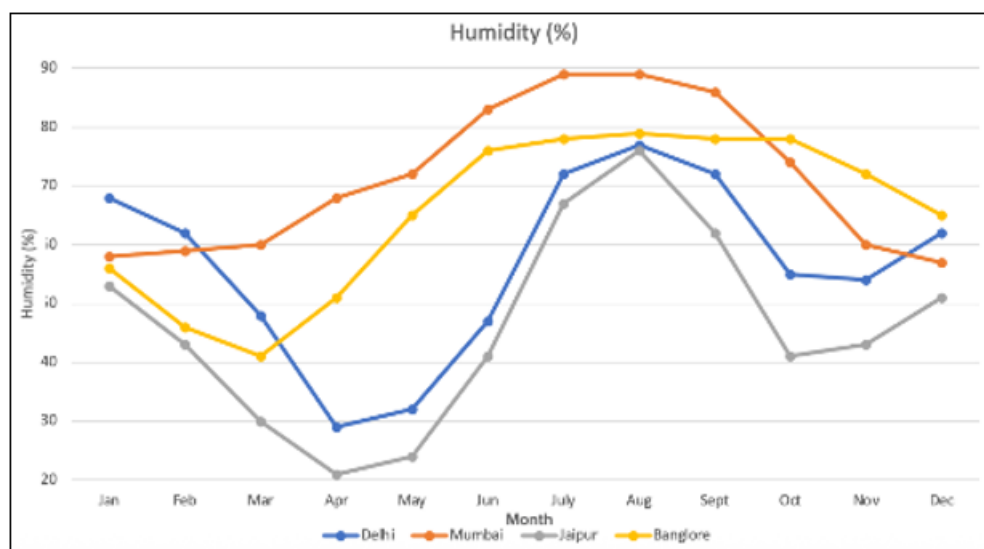


Figure 6: Month-wise average humidity of Delhi, Mumbai, Jaipur and Bangalore over the year

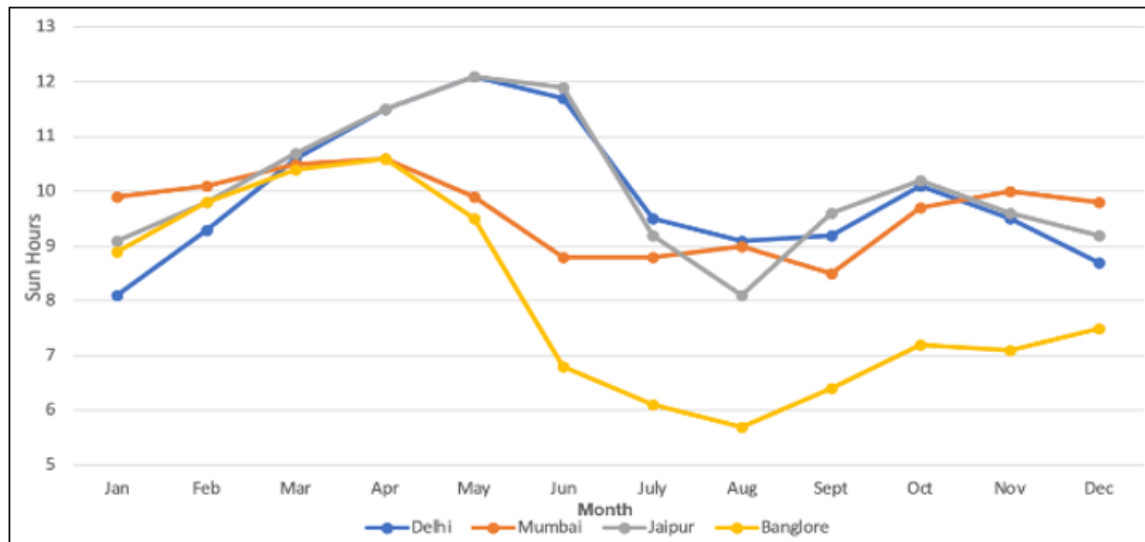


Figure 7: Month-wise average sun hours of Delhi, Mumbai, Jaipur and Bangalore over the year

Effect of Humidity and Sunshine Hours on Photovoltaic Efficiency

Humidity influenced photovoltaic performance indirectly by affecting atmospheric transparency and cloud formation (A. Ghosh, 2020). Figure 6 shows that Mumbai recorded the highest humidity levels, reaching 89% during July and August, while Figure 5 indicates that pollution-adjusted efficiency remained relatively high because pollution levels were comparatively low. Similarly, Figure 6 shows that Bangalore reached humidity levels of approximately 86% during the monsoon season, yet Figure 5 demonstrates that it maintained the highest pollution-adjusted efficiencies. In contrast, Figure 6 indicates that Jaipur experienced very low humidity levels (22–25% during April and May), although

Figure 8 shows that efficiency gains were limited due to elevated cell temperatures observed in Figure 4.

Sunshine duration also influenced photovoltaic performance. Figure 7 shows that Delhi recorded the highest sunshine duration at 12.1 hours per day in May, while Bangalore reached 11.5 hours per day in April. However, despite these favourable sunshine conditions, Figures 2 and 5 demonstrate that severe pollution in Delhi substantially reduced effective PV efficiency. Overall, humidity and sunshine duration had a smaller influence on PV performance than temperature and air pollution, which is consistent with previous studies (A. Ghosh, 2020; Baghel & Chander, 2022).

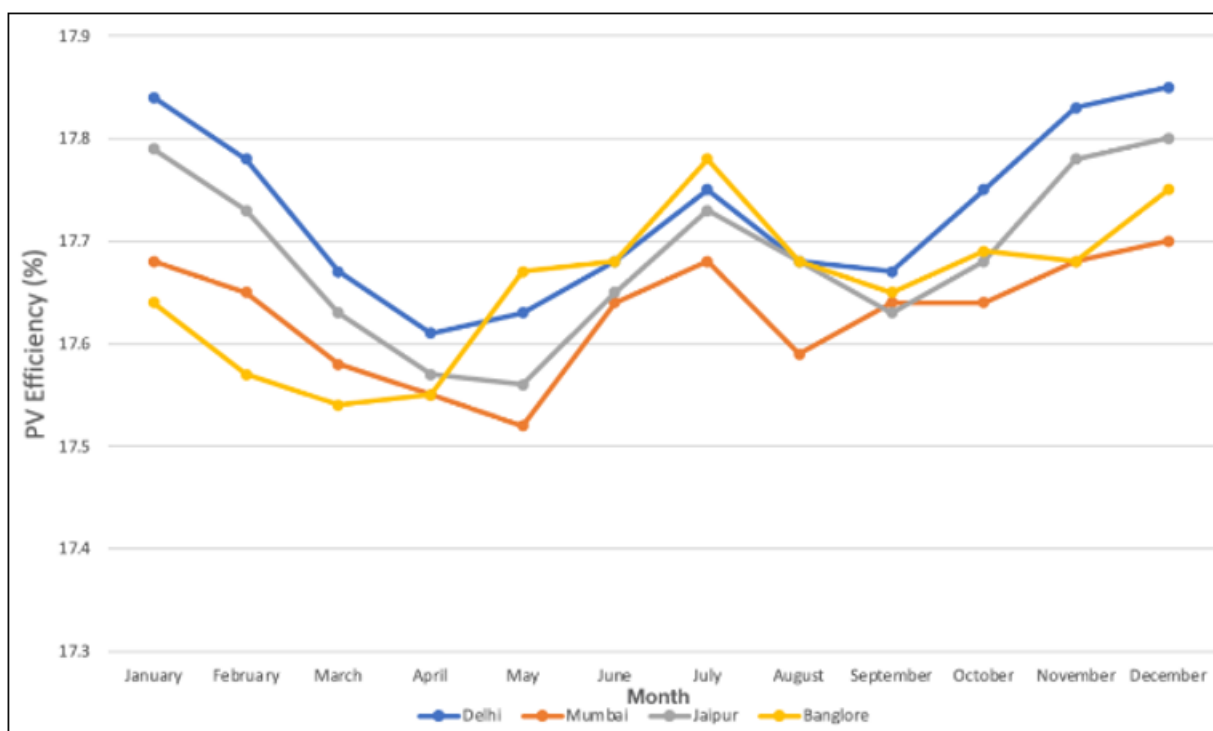


Figure 8: Month-wise PV Efficiency of Delhi, Mumbai, Jaipur and Bangalore over the year

Comparison of Photovoltaic Performance Across Cities

Figure 5 shows that Bangalore demonstrated the strongest overall performance, with pollution-adjusted efficiencies

remaining above 16.66% throughout the year and reaching 17.34% in July. Figures 5 and 6 indicate that Mumbai showed the second-best performance despite experiencing the highest

humidity levels, suggesting that humidity alone does not significantly reduce efficiency when pollution concentrations remain low. Figures 1, 2, 4 and 5 show that Jaipur benefited from high solar irradiation and low humidity but experienced reduced performance due to elevated temperatures and increasing PM2.5 concentrations. In contrast, Figures 2 and 5 demonstrate that Delhi exhibited the poorest overall performance, with pollution-adjusted efficiency declining from 17.31% in July to approximately 13.4% during November and December because of severe pollution events. Overall, these findings agree with previous studies showing that cities with higher pollution levels experience greater reductions in photovoltaic performance than cleaner urban environments (S. Ghosh et al., 2023; Sethi & Kosmopoulos, 2025).

5. Conclusion

This study investigated the impact of urban pollution and climatic conditions on photovoltaic (PV) efficiency across four major Indian cities: Delhi, Mumbai, Jaipur, and Bangalore. The objective was to determine how environmental variables, including temperature, PM2.5 concentration, humidity, solar irradiation, sunshine hours, and cell temperature, influence photovoltaic performance and to identify which factors have the greatest effect on solar energy generation.

The results showed that both climatic conditions and air pollution affect PV efficiency, although their impacts vary significantly between cities. Higher cell temperatures were generally associated with small reductions in photovoltaic efficiency, while increased solar irradiation and sunshine hours supported greater energy generation. Humidity was found to have a moderate indirect effect by influencing atmospheric transparency and cloud formation, but its impact was less significant than other environmental variables. Air pollution, particularly PM2.5 concentration, produced the largest reductions in effective photovoltaic performance, with Delhi experiencing the greatest efficiency losses during periods of severe pollution. In contrast, Bangalore consistently demonstrated the strongest overall performance due to its low pollution levels, moderate temperatures, and stable climatic conditions.

These findings highlight the importance of considering both climatic and air-quality factors when assessing the performance and viability of photovoltaic systems in urban environments.

As solar energy adoption continues to expand across India, incorporating pollution and climate data into photovoltaic planning, modelling, and system design could improve energy forecasts and support the development of more efficient and sustainable solar infrastructure.

References

- [1] E. Prasanthi, Performance Evaluation of Solar PV Panels Under Different Environmental Conditions in Southern India (2025). https://ijersem.com/wp-content/uploads/2025/12/41519-Performance_Evaluation_of_Solar_Photovoltaic_Panel_s_Under_Different_Environmental_Conditions_in_Southern_India.pdf
- [2] N. S. Baghel & N. Chander, "Performance comparison of mono and polycrystalline silicon solar PV modules under tropical climatic conditions in east-central India," *Clean Energy*, 2022. <https://academic.oup.com/ce/article/6/1/165/6532457>
- [3] S. Ghosh et al., "India's photovoltaic potential amidst air pollution and land constraints," *iScience*, 2023. <https://www.sciencedirect.com/science/article/pii/S2589004223019338>
- [4] S. Ghosh et al., "Cleaner air would enhance India's annual solar energy production by 6–28 TWh," *Environmental Research Letters*, 2022. <https://iopscience.iop.org/article/10.1088/1748-9326/ac5d9a>
- [5] A. Ghosh, "Soiling Losses: A Barrier for India's Energy Security Dependency from Photovoltaic Power," *Challenges*, 2020. https://www.researchgate.net/publication/341713694_Soiling_Losses_A_Barrier_for_India's_Energy_Security_Dependency_from_Photovoltaic_Power
- [6] R. Chawla et al., "Impact of Dust for Solar PV in Indian Scenario: Experimental Analysis" <https://www.igi-global.com/chapter/impact-of-dust-for-solar-pv-in-indian-scenario/226919>
- [7] D. Sethi & P.G. Kosmopoulos (2025), "Rooftop Solar Photovoltaic Potential in Polluted Indian Cities: Atmospheric and Urban Impacts, Climate Trends, Societal Gains, and Economic Opportunities" <https://www.mdpi.com/2072-4292/17/7/1221>
- [8] M. H. Bergin et al., "Large Reductions in Solar Energy Production Due to Dust and Particulate Air Pollution," *Environmental Science & Technology Letters*, 2017. <https://pubs.acs.org/doi/full/10.1021/acs.estlett.7b00197>
- [9] S. Ghosh et al., "Future photovoltaic potential in India: navigating the interplay between air pollution control and climate change mitigation," *Environmental Research Letters*, 2024. <https://iopscience.iop.org/article/10.1088/1748-9326/ad8c68>
- [10] B. Patnaik et al., "An Experimental Study of Greenhouse Gas Concentration on the Maximum Power Point of Solar PV Panels," *Engineering, Technology & Applied Science Research*, 2020. <https://etasr.com/index.php/ETASR/article/view/3682>
- [11] Bamisile, O., Acen, C., Cai, D., Huang, Q., & Staffell, I. (2025). The environmental factors affecting solar photovoltaic output. *Renewable and Sustainable Energy Reviews*, 208, 115073. <https://doi.org/10.1016/j.rser.2024.115073>
- [12] Dudáš, A., Udristoiu, M. T., Alkharusi, T., Yildizhan, H., & Sampath, S. K. (2024). Examining effects of air pollution on photovoltaic systems via interpretable random forest model. *Renewable Energy*, 232, 121066. <https://doi.org/10.1016/j.renene.2024.121066>
- [13] Skoplaki, E., & Palyvos, J. A. (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar Energy*, 83(5), 614–624. <https://doi.org/10.1016/j.solener.2008.10.008>