



Improved lifespan of photovoltaic devices based on ZnO nanorods/p-silicon heterostructures using active air convection cooling systems: a comparative degradation study

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ABSTRACT

Nanostructured solar cells offer substantial advantages in terms of material efficiency and streamlined fabrication techniques; however, their operational reliability at elevated temperatures remains a critical challenge. This study, for the first time, evaluates the influence of forced air convection cooling on the operational longevity and stability of nanostructured heterojunction photovoltaic devices fabricated on zinc oxide nanorods. Here, a ZnO buffer layer was initially deposited to form a heterojunction with Si substrate, followed by the development of zinc oxide nanorods designed to enhance photon absorption. Two identical solar cells were fabricated and subjected to continuous solar irradiation for 30 days; one was actively cooled using a forced air system, while the other was left uncooled. Post-exposure characterization proved that the morphology and optical characteristics of the cooled nanorods remained largely intact, underscoring the significance of thermal management in maintaining the performance of nanostructured photovoltaic devices. The reference cells without cooling exhibited a 7.4% efficiency loss after 30 days of continuous operation, due to elevated temperatures causing structural changes in the ZnO nanorods. The fan-cooled devices maintained more stability during the same period, with a 2.0% decrease in efficiency. The microstructural evaluation of cooled devices revealed that their nanorod structure remained intact with minimal damage. The results showed

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that heat management strategies enhance the reliability and operational lifespan of nanostructured photovoltaic devices.

1 Introduction

Global energy demand continues to climb, with estimates up to 75% rise by 2050 [1]. This increased need and environmental concerns about traditional energy sources have pushed research into low-carbon renewable energy alternatives. Because photovoltaic (PV) technology is inexpensive, widely available, and environmentally friendly, it has become a promising renewable energy source [2]. Over the last decade, the worldwide photovoltaic market has grown more than 50-fold [3].

Recent advances in photovoltaic technology have led to the development of various types of solar cells, ranging from traditional silicon-based cells to low-dimensional technologies. Nanostructured and thin film solar cells, particularly those based on zinc oxide (ZnO) nanostructures, have garnered significant attention due to their specific nature properties, such as high carrier mobility, broad bandgap, elevated exciton binding energy, and relatively simple fabrication processes [4, 5]. These features make ZnO nanostructure-based solar cells interesting candidates for next-generation photovoltaic systems, potentially requiring less material and manufacturing costs than current silicon-based cells [6]. Despite these advantages, the widespread commercial deployment of solar cells based on nanostructures faces various barriers, the most significant of which are thermal stability and operational longevity. [7]. As the operational temperature rises, all PV systems experience a decline in conversion efficiency, with crystalline silicon cells losing an average of 0.4–0.5% per degree Celsius [8]. Nanostructured materials exhibit even higher temperature sensitivity because of their higher surface area and metastable morphology [9]. Several researchers have investigated thermal-induced deterioration mechanisms in ZnO nanostructures. Wang et al. [10] found that prolonged exposure to high temperatures produces considerable morphological changes in ZnO nanorods, including coalescence and loss of well-defined nanostructures. Similarly, Pradhan et al. [11] found that

temperature stress increases interfacial deterioration in ZnO-based photovoltaic devices. Another report showed that photoluminescence quenching occurs in ZnO nanostructures during continuous operation at high temperatures, indicating a degradation of optical characteristics critical to photovoltaic efficiency [12].

Several cooling solutions have been investigated to decrease the heat degradation of solar modules. Water cooling technologies, such as front surface cooling, rear surface cooling, and immersion cooling, have been widely studied and proven to increase both the immediate efficiency and long-term stability of conventional solar panels [13–15]. Krauter found that employing water film cooling on ordinary PV panels increased electrical power output by 10.3% over a full day [13]. In a similar study, Bahaidarah et al. found that applying rear surface water cooling enhanced the photovoltaic performance by ~9% [14]. While water cooling has proven to be successful, it presents several obstacles, including water resource requirements, the potential for electrical risks, and maintenance issues associated with scaling and corrosion [16]. Air cooling provides an alternative solution that overcomes these restrictions. Bahri-zadeh et al. [17] found that forced air cooling can lower the temperature of PV modules, resulting in a 1.6% increase in efficiency. However, there is a large research gap in the application of forced air cooling to the lifespan of solar cells, particularly for nanostructured devices, where temperature sensitivity and degradation mechanisms differ dramatically from those of traditional silicon-based technology.

This paper addresses the research gap by examining the influence of the air-cooling system on the long-term stability and performance of ZnO nanorod-based heterojunction solar cells. Unlike prior studies, which have primarily focused on rapid efficiency increases, this research shows the effect of heat management on the optical stability of zinc oxide nanorods and its subsequent effect on device longevity over an extended operational period. Here, a comparison of efficiency degradation rates

between actively cooled and reference devices, along with morphological analysis and photoluminescence measurements, is presented to investigate the degradation mechanisms.

2 Experiment

A typical RCA process was used to chemically clean a 50 mm by 50 mm single-crystal p-type silicon substrate with a resistance of $0.3 \Omega \text{ cm}$ in order to eliminate surface contaminants [18]. Thermal evaporation created a $0.25 \mu\text{m}$ -thick Al layer on the wafer's back side, which was then heated at 450°C for 20 min in nitrogen to form a p^+ layer. This layer acts as an ohmic metal junction in photovoltaic devices. The ZnO buffer layer was then sputter-deposited on the upper surface of the silicon substrates. In the vacuum chamber, the distance between the target and the substrate was set to 100 mm, and an argon pressure of 6.2×10^{-3} mbar was applied (working pressure). Sputtering at a power of 140 W for 28 min produced ZnO layers with a thickness of 100 nm. To enhance the physical quality of the ZnO layer, sputtered samples were annealed for 60 min in an Ar environment at 350°C . Next, chemical bath deposition process at 90°C for 2 h, using hexamethylenetetramine and zinc nitrate with an equal molar concentration of 0.03 M, resulted in the development of zinc oxide nanorods on the substrate.

To build the devices, Au top electrodes were positioned on the substrate (window area = 122 mm^2). Annealing for an hour at 200°C in an argon environment in a tube furnace reduced the mismatch between the top contacts and the substrate. For the forced air-convection cooling system, a centrifugal electric fan with an input power of 1.0 W, a speed of 5000 RPM, and an airflow of $0.28 \text{ m}^3/\text{min}$ was positioned at the backside of the devices. Two devices were created: one with an electric fan cooling system and one without (reference group). The entire experiment was repeated for five sets of devices, each containing two identical samples (fan-equipped and uncooled) fabricated in the same batch. All of the devices were exposed to natural sunlight for 30 days under similar conditions. The temperature of the devices was monitored using a calibrated non-contact infrared thermometer. The current–voltage (J – V) diagrams of both as-fabricated and 30-day-used devices were compared using a source-meter to assess their photovoltaic characteristics. These observations were conducted under controlled

conditions using an AM 1.5 solar light simulator. The J – V curve data obtained from both device sets (with and without cooling fans) were used to calculate performance characteristics.

3 Results and discussion

Figure 1 shows the top-and side-view FESEM micrographs of ZnO nanorods before and after 30 days of operation under sunlight. Figure 1a illustrates the top-view morphology of the freshly synthesized sample, whereas Fig. 1b and c are captured after 30 days of operation under sunlight exposure for the non-cooled and cooled conditions, respectively. Figure 1a depicts the homogeneity of the synthesized arrays with a mean size of $\sim 65 \text{ nm}$. It demonstrates the successful growth of compact, hexagonal, and homogeneous zinc oxide nanorods. In contrast, the aging of nanostructures due to working in ambient conditions for 30 days is demonstrated in Fig. 1b. Here, the evidence of coalescence and merging of nanorods is attributed to exposure to higher temperatures. The high ratio of surface to volume and increased exposed area of nanostructures facilitate their interaction with the environment, resulting in accelerated aging under prolonged illumination. The top view of the device equipped with the cooling system, however, shows a higher degree of stability compared to the one for the non-cooled sample. Here, the shape of the nanorods remains comparable to that of the freshly synthesized sample (Fig. 1a). The side-views of the as-prepared sample (Fig. 1d) and the one with the cooling system after 30 days of sunlight exposure (Fig. 1f) are also similar. It confirms that the physical skeleton of parallel ZnO nanorods, with an average length of approximately 0.5 microns, was preserved by controlling the working temperature. However, the cross-sectional view of the sample without cooling systems shows evidence of damage and cracks in the nanorod structure. It indicates that the cooling system was effective in maintaining the integrity of the nanostructures. Thus, active air-cooling and reducing the working temperature of samples have a direct impact on preserving the exposed area of nanostructures after prolonged exposure to light.

To better understand the effect of 30 days of operation on species distribution across the ZnO/Si interface, cross-sectional elemental mapping was performed using energy-dispersive X-ray spectroscopy (EDS).

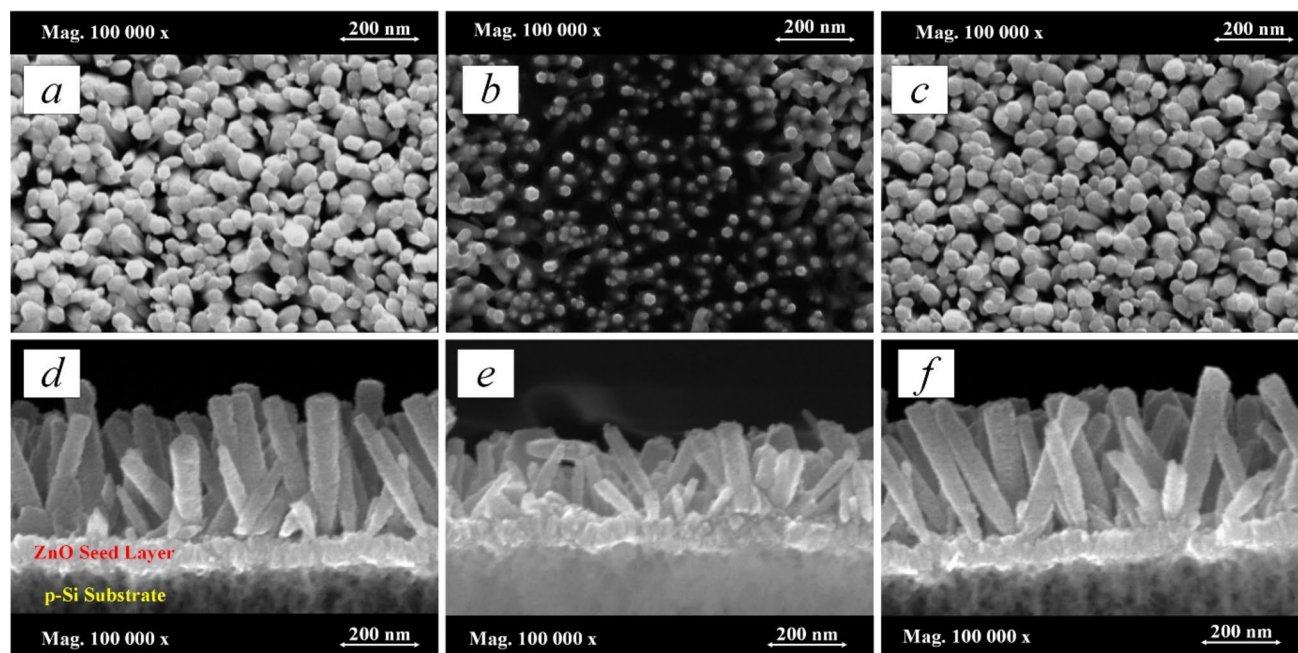


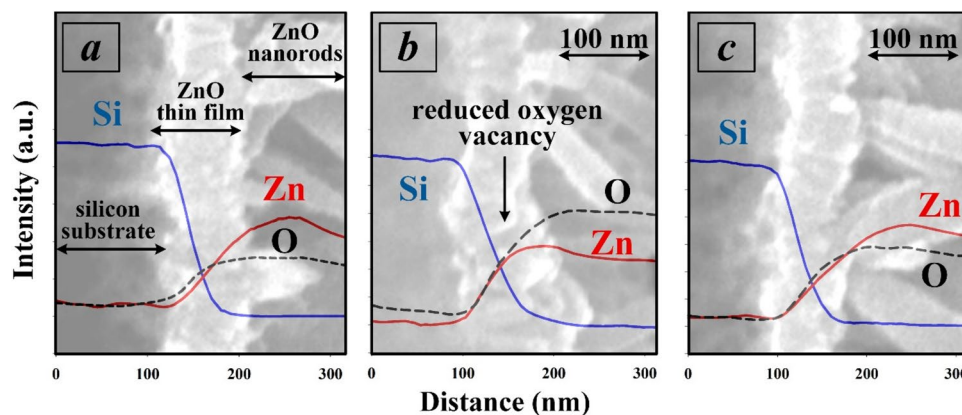
Fig. 1 FESEM micrographs showing the planar and cross-sectional views of freshly prepared (a, d) and used ZnO nanorods after 30 days of operation under sunlight, without (b, e) and with (c, f) cooling systems

The elemental maps were recorded immediately after fabrication and again after 30 days of continuous light exposure, for both the cooled (fan-equipped) and uncooled devices, and are shown in Fig. 2. The EDS maps confirm the spatial overlap of Zn, O, and Si species across the ZnO/Si interface in both device configurations. The comparison of the elemental maps before and after 30 days of operation reveals a distinct difference between the two samples. In the uncooled device (Fig. 2b), prolonged exposure to elevated operating temperatures led to a reduction in oxygen vacancies accompanied by an increased oxygen concentration within the ZnO layer. This redistribution of oxygen

species at the junction interface directly increases ZnO's resistivity, degrading carrier transport across the ZnO/Si heterojunction and potentially contributing to a decline in device performance over time. In contrast, the cooled sample (Fig. 2c) retains a more stable elemental distribution across the interface after 30 days, showing its superior long-term reliability. Nevertheless, a moderate increase in oxygen concentration is still observed relative to the as-fabricated baseline (Fig. 2a), indicating that oxygen vacancy filling is not entirely eliminated but saturates at lower rates.

To further investigate the chemical states of oxygen and verify the elemental redistribution observed

Fig. 2 The cross-sectional energy-dispersive X-ray spectroscopy (EDS) mapping across the ZnO/Si interface for freshly prepared (a) and exposed ZnO nanorods without (b) and with (c) cooling system after 30 days of operation



by EDS, X-ray photoelectron spectroscopy (XPS) was performed on the O 1s core level, and the corresponding spectra are presented in Fig. 3. The O 1s spectra were deconvoluted into three components located at approximately 530.1, 531.3, and 533.2 eV, which are assigned to lattice oxygen in the ZnO crystal lattice, oxygen vacancy-related oxygen, and chemisorbed oxygen species, respectively. The as-prepared sample exhibits a pronounced oxygen vacancy component, indicating a relatively high concentration of intrinsic defects within the ZnO nanorods. These oxygen vacancies act as shallow donor states that increase the electron concentration and enhance the electrical conductivity of ZnO, facilitating carrier transport across the ZnO/Si heterojunction. Such defect-assisted conductivity is beneficial for the initial photovoltaic performance of the device by reducing the series resistance of the electron transport layer.

After 30 days of continuous operation without cooling, a noticeable reduction in the oxygen vacancy-related peak intensity is observed, accompanied by a relative increase in the lattice oxygen contribution. This trend indicates that oxygen atoms gradually occupy vacant lattice sites during prolonged operation, particularly under elevated operating temperatures. The filling of oxygen vacancies reduces the concentration of donor-like defects, thereby decreasing the free electron density and increasing the resistivity of the ZnO nanorods. This observation is in agreement with the EDS elemental mapping results (Fig. 2b), which showed an increased oxygen concentration within the ZnO layer after long-term operation. In contrast, the cooled device exhibited lower reduction in the oxygen vacancy concentration after the same operating period, while maintaining an O 1s spectrum closely

resembling that of the as-prepared sample. The forced air-cooling system suppresses excessive temperature rise during operation, thereby reducing thermally activated oxygen diffusion and limiting the occupation of oxygen vacancy sites. Although a small increase in lattice oxygen is still expected due to prolonged exposure to ambient conditions and continuous illumination, the preservation of a higher oxygen vacancy concentration helps maintain the electrical conductivity of the ZnO nanorods and minimizes deterioration of the heterojunction.

Figure 4a compares the absorption spectra of ZnO nanorod samples. The highest optical absorbance was recorded at 570 nm for all three samples. The maximum absorbance of the freshly prepared sample was 85%. After 30 days of operation, this value was reduced to 74% and 82% for the samples without and with an active air-cooling system, respectively. Due to their enhanced surface area, the as-prepared nanostructures are capable of capturing a greater number of photons. Therefore, their photon absorption coefficients are greater than that of the other samples. In this sample, the specific morphology of the well-aligned nanorods provides multiple scattering of incident light, thereby improving their light-entrapment properties. The deducted rate of light absorption for the other samples conforms to their morphologies and is attributed to structural deviations after 30 days of working under various temperatures. However, the rate of absorption reduction for the sample equipped with the cooling system is lower than that of the uncooled samples. Therefore, this sample demonstrated greater stability in photon absorption due to the control of working temperature achieved through the active air-cooling technique.

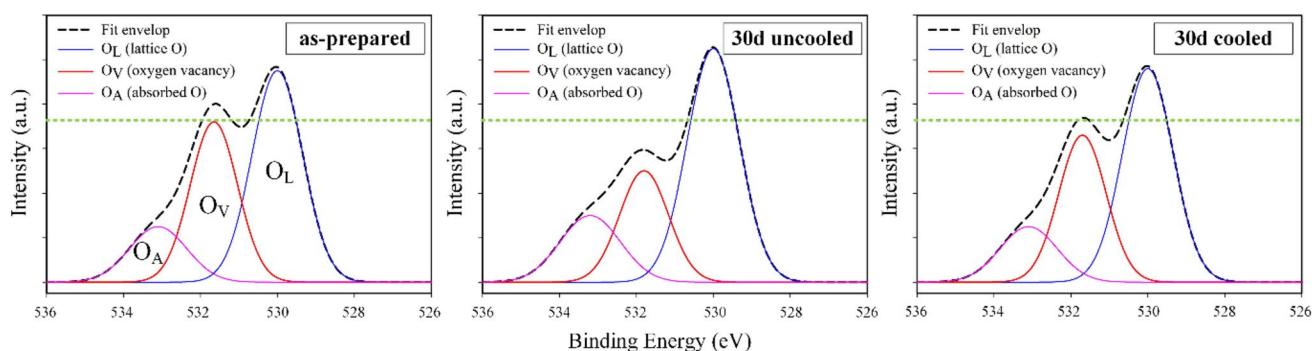


Fig. 3 XPS spectra of ZnO nanorods for the as-prepared, 30-day cooled, and 30-day uncooled samples. The O 1s spectra were deconvoluted into three components corresponding to oxygen vacancies (O_V), lattice oxygen (O_L), and adsorbed oxygen species (O_A)

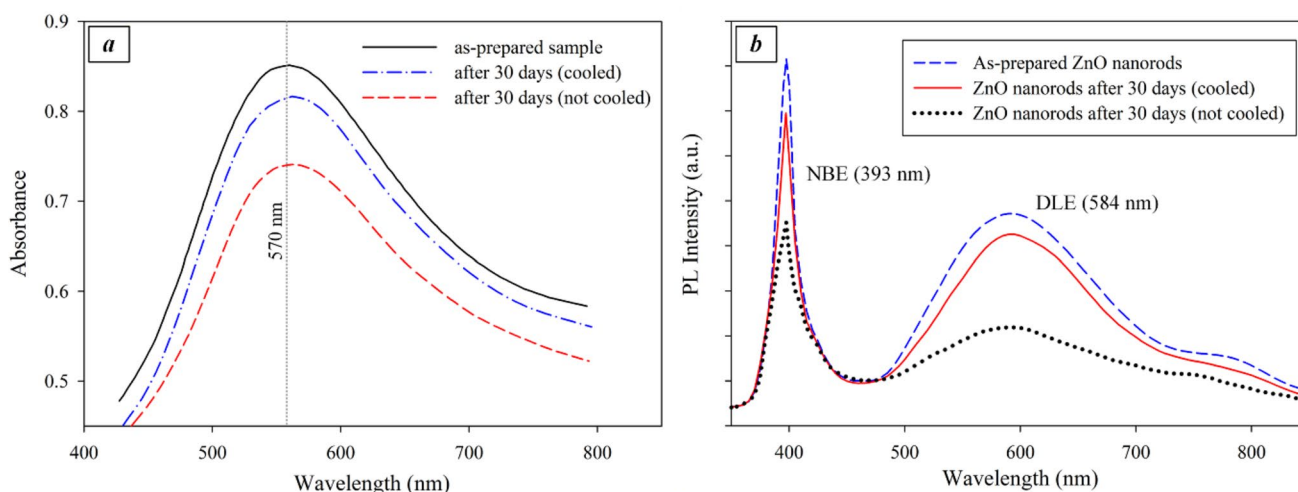


Fig. 4 (a) The optical absorption spectra for the freshly synthesized and used ZnO nanorods with and without the forced air-cooling system. (b) The photoluminescence curves of ZnO nanorods before and after 30 days of operation under sunlight

Next, the photoluminescence (PL) spectra of three different samples were recorded at ambient conditions and are shown in Fig. 4b. The freshly prepared ZnO nanorods sample exhibited a sharp, intense near band edge (NBE) peak at 393 nm, accompanied by a wide visible emission from 480 to 730 nm. The NBE peak correlates to the recombination of photo-induced carriers across the broad bandgap of zinc oxide nanorods [19]. In contrast, the visible peak is linked to deep-level emission (DLE) transitions caused by the interstitials and oxygen vacancies [20]. The PL spectra of the used samples (after 30 days of light exposure) exhibited the same peaks but with lower intensities. Here, under prolonged exposure to ambient conditions, the intrinsic oxygen vacancy sites within ZnO nanorods were occupied partially through oxygen absorption from the environment (as seen in Figs. 2 and 3). The higher working temperature facilitated the absorption of oxygen and reduced the DLE intensity for the uncooled nanostructures more significantly compared to the fan-equipped sample, leading to a ~67% decrease in the DLE intensity. In contrast, the DLE emission for the cooled sample declined by ~13% compared to the fresh sample. In the NBE transition, an intensity decrease of ~51% was observed for the uncooled sample, while the intensity of this peak for the cooled sample was ~16% lower than that of the freshly prepared

at cooled and uncooled conditions, displaying a sharp, intense near-band edge (NBE) peak at 393 nm and a broad visible deep-level emission (DLE) range from 480 to 730 nm, with a peak at 584 nm

sample. The significant reduction in NBE emission after 30 days of operation without a cooling system is attributed to the high working temperature's impact on the morphology deviation of nanorods, resulting in their reduced exposed area and lower absorption coefficient compared to the fresh sample. After 30 days of working at ambient temperature, the sample's ability to capture incident photons was reduced, resulting in a lower rate of electron-hole generation under laser excitation beam and a decline in the NBE intensity. However, the spectrum for the fan-equipped sample shows that the active air-cooling system can minimize PL quenching by controlling the working temperature of ZnO nanorods and preserving the optical characteristics of the samples. Here, the NBE intensity for this sample is comparable to that of the fresh nanostructures due to its relatively high surface area and stable photon-capturing ability.

The NBE peak positions remained intact for all three samples. Therefore, the crystallite size of the nanostructures remained constant despite working at different temperatures. The quantum confinement (QC) states that the decrease in the nanostructures' crystallite size produces bandgap broadening, which results in a PL blueshift [21]. This theory states that the nanostructures' confined bandgap relies on their crystal size, which the following equation can describe [22]:

$$E_g^N = (h^2/8d^2)[(1/m_h^*) + (1/m_e^*)] + E_g^B \quad (1)$$

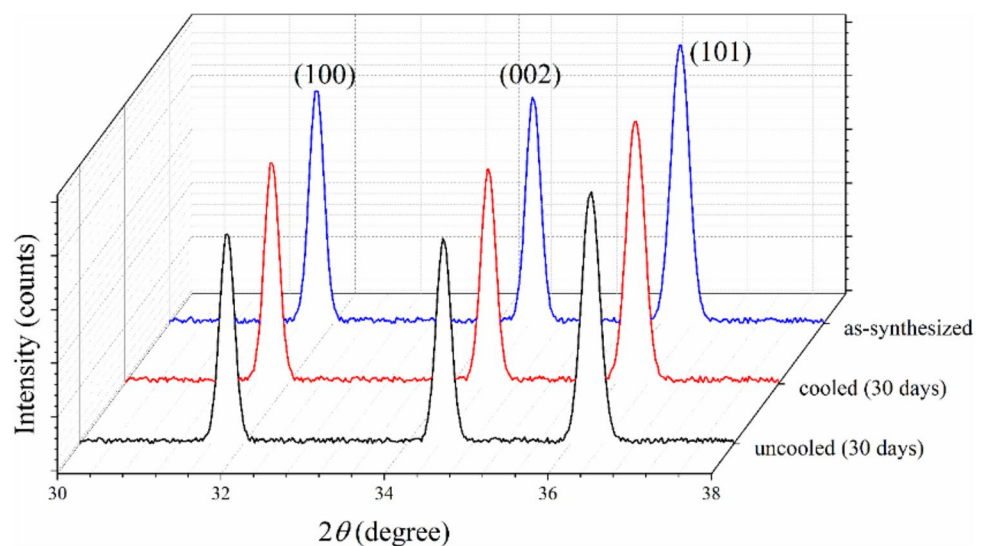
where d is the crystal size, E_g^B is the bandgap of the material (bulk), while E_g^N is the nanostructures' confined bandgap, m_h^* and m_e^* are the effective mass of hole and electron, respectively. Here, the PL peak position was fixed after working at various temperatures. Therefore, the crystal size of the nanostructures remained unchanged after working under different conditions. Coalescence in the ZnO nanorods primarily involves the fusion of the nanorods' grain boundaries, yet the interior defect landscape and the nature of the dominant radiative recombination centers may not change fundamentally. Here, agglomeration altered the morphology and grain boundary density but did not restructure the electronic states responsible for luminescence. The PL peak position reflects the energy gap between the emitting and the recombination states. Therefore, as long as these states are structurally robust and the crystallite size of the samples is not altered by the thermal conditions driving coalescence, the PL peak position remains unchanged.

The structural stability was further confirmed by X-ray diffraction (XRD) measurements. Figure 5 shows the diffraction patterns of the as-prepared sample and the samples exposed for 30 days with and without fan cooling. In all samples, the ZnO nanostructures show a wurtzite hexagonal structure with a dominant peak at $2\theta = 36.25^\circ$ related to a d -spacing of 2.48 Å. According to the standard JCPDS database (card number: 089-0510), this peak is assigned to the (101) orientation of the ZnO wurtzite hexagonal structure. No phase

variation was detected after the 30 days of exposure under sunlight for both cooled and uncooled samples. However, the peak intensities of the used sample were slightly lower than that of the freshly prepared sample. The full peak width at half-maximum intensity (FWHM) of the dominant peak remained unchanged which can be assigned to the similar crystallite size (4.32 ± 0.02 nm) of the ZnO samples based on the Scherrer's equation ($D = 0.9\lambda/\beta \cos \theta$), where D is the crystallite size, λ is the incident X-ray wavelength (Cu K $\alpha = 1.54$ Å), θ is the diffraction angle, and β is the FWHM of the diffraction peak [23]. The results exhibit identical lattice spacing, crystallinity, and structural quality of the cooled and uncooled ZnO nanorods before and after exposure to sunlight for 30 days, without detectable peak shift or additional diffraction peaks, indicating that no phase transformation or significant lattice distortion occurred during outdoor exposure. This observation is consistent with the unchanged near-band-edge PL emission.

Figure 6 shows the optoelectrical properties of the generated photovoltaic cells based on various ZnO nanorods/Si heterostructures. Figure 6a and b depict the band diagrams of zinc oxide and silicon heterojunctions before and after contact, respectively, to explain the charge transferring mechanism in the produced solar devices. As shown in Fig. 6a, the difference in bandgap energies between the zinc oxide n -type layer (~ 3.3 eV) and the silicon substrate (~ 1.9 eV) causes band edge discontinuity prior to contact [24]. Following contact, the asymmetric nature of the semiconductor interfaces caused by Fermi-level

Fig. 5 X-ray diffraction patterns of ZnO nanorods before and after 30 days of sunlight exposure with and without fan cooling. All samples exhibit wurtzite ZnO indexed to the (100), (002), and (101) crystal planes



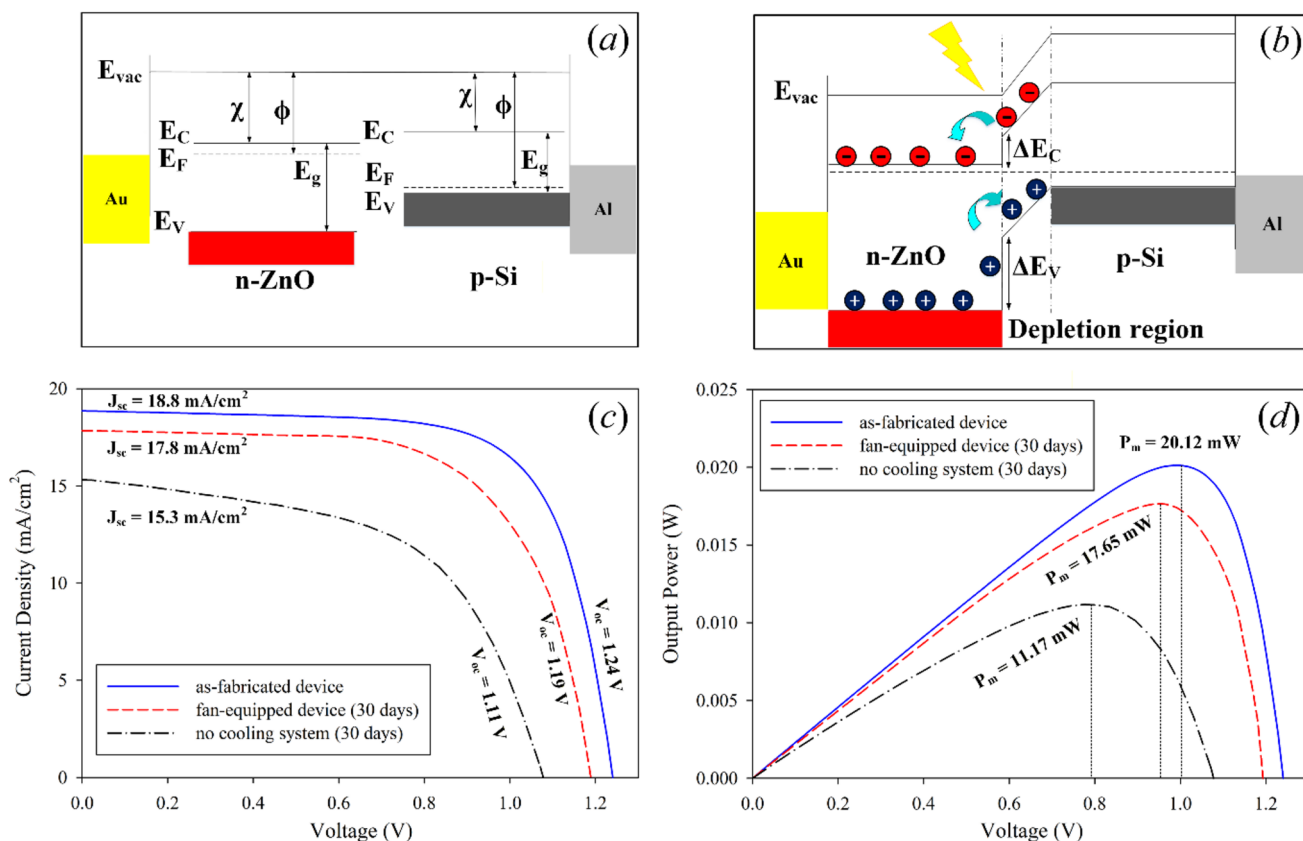


Fig. 6 The photovoltaic properties of fabricated nanostructured solar cells based on ZnO nanorods/p-silicon heterostructures; the bandgap diagrams (a) before contact, and (b) after contact, (c)

the J - V curves, and (d) the P - V curves for the devices before and after 30 days of operation under sunlight with and without active air-cooling system

alignment causes the conduction band (CB) in the Si substrate to bend downward in comparison to the ZnO thin film (Fig. 6b) [25]. Therefore, because of an electric potential at the p - n heterojunction, the electrons and holes are divided, resulting in a depletion region. Photogenerated excitons are created in the depletion region when exposed to light, which causes holes to move into the valence band of the p -Si substrate and electrons to migrate into the ZnO conduction band [26]. Electrons in the circuit are transported by the electric voltage produced by the charge accumulating on both sides of the solar cell device. This band diagram represents an ideal device, free from dislocations and structural defects. However, charge carrier recombination results from the availability of interbands brought on by structural flaws in manufactured devices, which lowers power conversion efficiency. Figure 6c compares the current density–voltage curves of freshly prepared and used devices after 30 days of operation with and without the air-cooling system.

The data represent the average values obtained from five independent sample sets, each including two devices (one fan-equipped and the other without a fan). The maximum photocurrent was observed for the newly prepared device at room temperature under the sun simulator's illumination. The device's maximum absorption coefficient and increased surface-to-volume ratio caused enhanced photon-capturing capability and increased light-induced exciton generation. The influence of exposure to sunlight for 30 days at ambient conditions is shown in the curves related to the uncooled and fan-equipped devices. The generated photocurrent in used devices is less than that in fresh devices. However, the rate of reduction in the photocurrent produced by the uncooled device is more significant, resulting in lower photovoltaic performance after 30 days of operation under sunlight. The curves for the output electrical power of devices (Fig. 6d) revealed a significant decline of 44% in the maximum electrical power of the uncooled device

after 30 days of operation under sunlight. In contrast, the rate of power decrease for the fan-equipped solar cell was reduced to 12%, showing higher stability in the photovoltaic performance of this device.

The current–voltage data of photovoltaic cells were used to calculate their power conversion efficiency (PCE) and fill factor (FF) using the following equations [27]:

$$FF = \frac{P_m}{I_{SC} \times V_{OC}} = \frac{J_m \times V_m}{J_{SC} \times V_{OC}} \quad (2)$$

$$\eta = V_{OC} \times I_{SC} \times FF / P_{in} \quad (3)$$

Here, P_m and P_{in} are the generated electrical power and the incident optical power, respectively. Table 1 provides the details of the photovoltaic parameters of the fabricated devices. The standard deviations were calculated from the mean value of each parameter across five sets of independently tested devices. It demonstrates that the η and FF of the uncooled device were significantly reduced after 30 days of operating under sunlight exposure, as evidenced by the substantial decrease in its photogenerated current density curve. The maximum efficiency of 16.5% was recorded for the freshly prepared device. While the efficiency of the uncooled device declined to 9.1% (efficiency loss of 7.4%) after 30 days of operation under ambient temperature. However, the efficiency reduction for the fan-equipped device was 2.0%, and this device exhibited a more stable efficiency of 14.5% over the same 30 working days, albeit at a lower working temperature due to the application of the active air-cooling system. This slight efficiency decline in the cooled sample aligns with the moderate increase in oxygen concentration at the ZnO/Si interface (as seen in Figs. 2 and 3) relative to the as-fabricated baseline, indicating

that oxygen vacancy filling is not entirely eliminated but occurs at a significantly lower rate. It should be noted that all devices were exposed simultaneously under identical outdoor environmental conditions during the 30-day aging test. Consequently, ambient humidity was the same for both the fan-equipped and uncooled devices. Since the electric fan only reduced the operating temperature and did not control humidity, the observed differences in device performance are primarily attributed to thermal management rather than variations in ambient humidity.

Figure 7 shows the capacitance–voltage (C – V) and dark current density–voltage (dark J – V) characteristics of the ZnO/Si heterojunction solar cells. The as-fabricated device exhibited the highest junction capacitance and the lowest dark current density, indicating superior junction quality, a narrower depletion region, and fewer electrically active interface defects. After 30 days of continuous operation, both the fan-equipped and uncooled devices exhibited reduction in capacitance accompanied by an increase in dark current, confirming that prolonged thermal exposure degrades the electrical properties of the heterojunction. The degradation was substantially more severe for the uncooled device, whereas the fan-equipped device retained significantly higher capacitance and lower dark current, demonstrating that active air-cooling effectively suppresses thermally induced junction degradation. Accordingly, the series resistance increased from $7.8 \, \Omega \, \text{cm}^2$ for the as-fabricated device to $8.6 \, \Omega \, \text{cm}^2$ for the fan-equipped device and $17.3 \, \Omega \, \text{cm}^2$ for the uncooled device, while the shunt resistance decreased from approximately $2.2 \, \text{k}\Omega \, \text{cm}^2$ to $1.8 \, \text{k}\Omega \, \text{cm}^2$ and $0.5 \, \text{k}\Omega \, \text{cm}^2$, respectively. The active air-cooling system reduced the effective performance-loss

Table 1 Photovoltaic parameters of devices based on zinc oxide nanorods/silicon heterostructures for freshly prepared and used devices with and without an active air-cooling system after 30 days of operation under ambient conditions

Devices	Short-circuit current (mA)	Open-circuit voltage (V)	Maximum power (mW)	Fill factor (FF)	Efficiency (%)	Efficiency loss (%)
As-fabricated device	23.0	1.24	20.12	0.70	16.5 ± 0.1	–
Fan-equipped device (after 30 days)	21.7	1.19	17.65	0.68	14.5 ± 0.1	2.0
Device without a cooling system (after 30 days)	18.7	1.11	11.17	0.54	9.1 ± 0.1	7.4

PCE data represent the average values obtained from five independent sample sets, with standard deviations calculated from the mean of each parameter across all sets

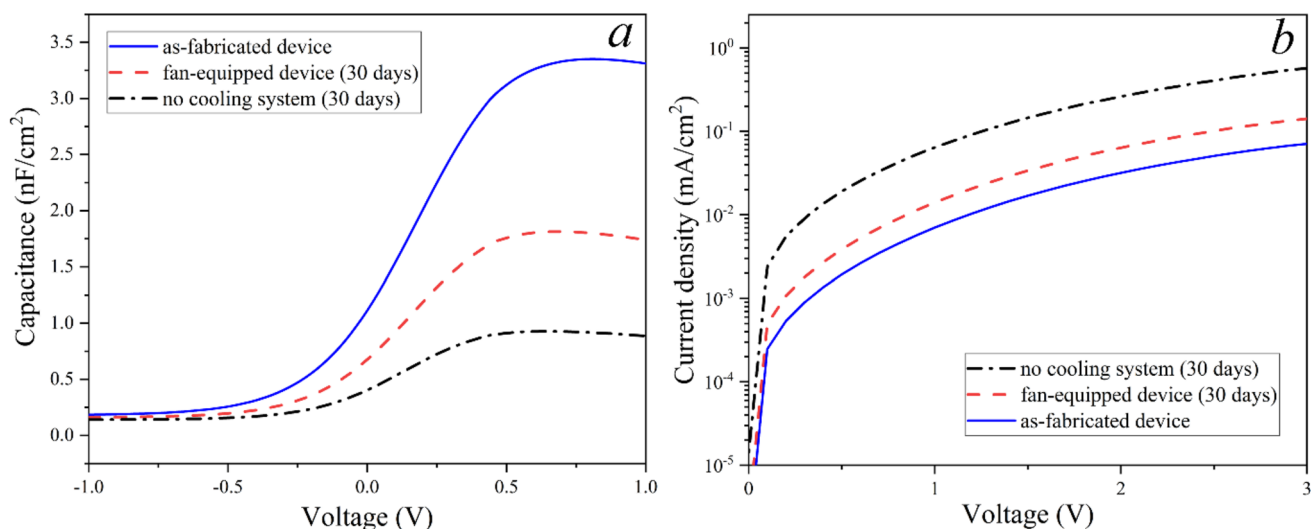
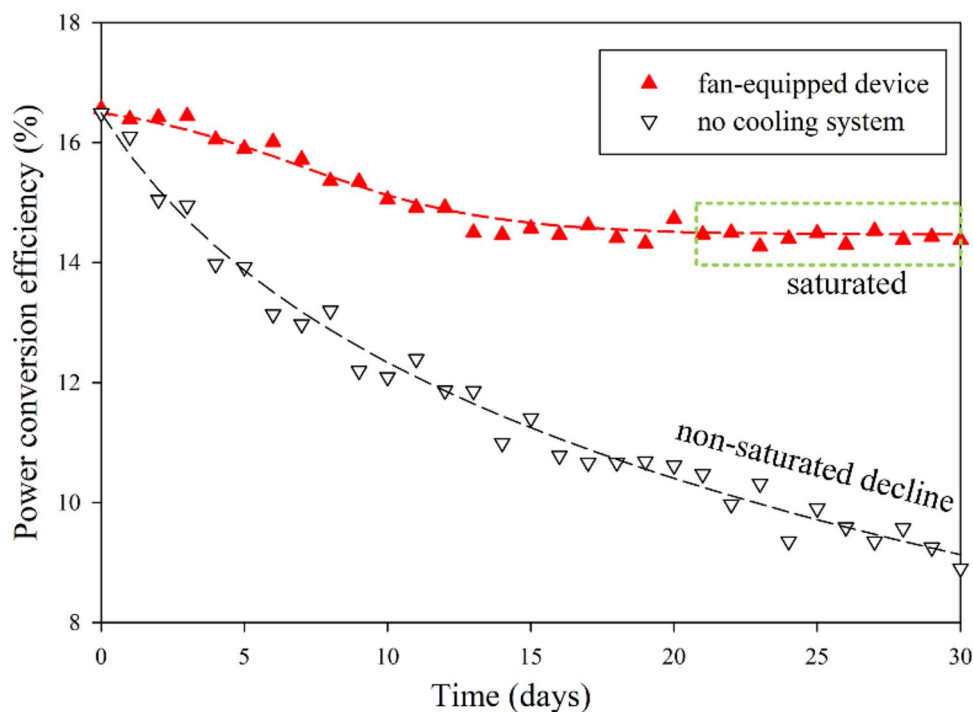


Fig. 7 (a) Capacitance–voltage (C – V) characteristics and (b) dark current density–voltage (dark J – V) characteristics of the as-fabricated, fan-equipped, and uncooled ZnO/Si heterojunction solar cells after 30 days of continuous operation

coefficient associated with operating temperature from approximately 0.61 to 0.17%/°C, corresponding to a 72.5% reduction in temperature-induced performance degradation. This improvement demonstrates that maintaining the device at a lower operating temperature effectively suppresses thermal degradation and preserves the long-term photovoltaic performance of the ZnO/Si solar cells.

To better understand the efficiency loss mechanisms of both devices over 30 days, the samples' efficiencies were measured daily. Figure 8 shows the daily decline in efficiency for both devices over a 30-day period. The trend for the uncooled sample indicates a steep decline, suggesting the reduction will continue beyond 30 days. Conversely, the cooled sample's reduction stabilized after a while, demonstrating greater

Fig. 8 The daily monitoring of efficiency degradation for fabricated solar cells with and without the forced air convection cooling system over 30 days of sunlight exposure



stability, which confirms the saturation of oxygen absorption in the ZnO nanostructures and provides a more stable performance in the fan-equipped device. Therefore, long-term exposure to elevated temperatures degrades solar cell efficiency through two concurrent mechanisms: deterioration of surface morphology, which reduces light absorption, and p–n junction degradation, which reduces the density of photogenerated carriers. Thus, reducing the working temperature using this simple yet efficient cooling system preserves the optical characteristics of ZnO nanorods, resulting in an outstanding improvement in the longevity and lifespan of generated solar cells based on ZnO nanostructures. These results demonstrate that reducing the operating temperature effectively suppresses thermally activated defect generation, limits the increase in dark current and series resistance, preserves junction quality, and significantly enhances the long-term stability of the ZnO/Si solar cells.

The photovoltaic characteristics of the fabricated ZnO nanorods/p-Si heterojunction solar cells were compared with those reported for similar ZnO nanostructure/p-Si heterojunction solar cells in recent literature, as summarized in Table 2. The comparison indicates that the fabricated devices exhibit superior photovoltaic performance in terms of power conversion efficiency, open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), and fill factor (FF). In addition to the favorable photovoltaic performance, the present study demonstrates the effectiveness of the proposed active air-cooling strategy in mitigating the degradation of ZnO nanorod-based heterojunction solar cells during prolonged outdoor exposure. Unlike previous studies, which primarily focus on improving the initial photovoltaic performance of ZnO nanostructure/p-Si

heterojunctions, this work systematically investigates the influence of thermal management on the long-term stability of the devices under realistic operating conditions.

Recent developments in hybrid cooling approaches, such as phase-change materials (PCMs) integrated with heat sinks, have shown promise in enhancing the thermal regulation of solar modules without excessive energy consumption. For instance, Rahman et al. (2023) demonstrated that coupling PCMs with air convection systems improved thermal stability by 17% under desert-like conditions, potentially extending device lifespans significantly [33]. Incorporating such hybrid methods with nanostructured devices like ZnO nanorods may present a viable route for achieving both passive and active heat mitigation strategies, thereby producing more durable nanostructure-based solar cells, and will be further studied.

4 Conclusion

The implementation of a forced air convection cooling system, employing a centrifugal electric fan affixed to the rear side of photovoltaic cells, has been demonstrated as an effective strategy for enhancing the operational lifespan of ZnO nanorod-based solar cells. Nanostructured solar devices were fabricated using nanorods developed on p-type silicon wafers via chemical bath deposition. The optical and photovoltaic properties of these devices were assessed immediately following fabrication and again after 30 days of continuous solar exposure under ambient conditions. To evaluate the cooling system's effectiveness, two identical devices were fabricated and exposed to

Table 2 A comparison between the photovoltaic parameters of this study and other similar reports on ZnO nanostructures/p-silicon solar cells

Type of solar cells	Fabrication techniques	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)	References
Ag/ZnO nanoflower/PS/Al	CBD, thermal evaporation	3.7	0.21	0.50	12.9	[28]
Au/rGO-ZnO/p-Si/Au	Sol–gel, Spin coating, thermal evaporation	14.5	0.52	0.52	4.3	[29]
Ag/ZnO nanorods/texture Si/Al	Sputtering, thermal evaporation	7.3	0.26	0.44	9.1	[30]
Al/Fluorine-doped ZnO/p-Si/Al	Sol–gel, ultrasonication, thermal evaporation	23.0	0.50	0.55	6.7	[31]
Al/ZnO/ZnO nanorods/ZnO seeds/p-Si/Al	Ultrasonication, ALD, hydrothermal, e-beam evaporation	35.10	0.44	0.71	10.9	[32]
Au/ZnO nanorods/ZnO thin film/p-Si/Al	CBD, sputtering	18.8	1.24	0.70	16.5	This study

sunlight; one equipped with an active fan system, the other serving as an uncooled reference. The morphology of the freshly fabricated sample revealed homogeneous, compact, and vertically aligned ZnO nanorods. This device exhibited high photon absorption (~ 68%), strong NBE photoluminescence, and a broad visible emission spanning 480–730 nm. The morphology and optical characteristics of the samples were recorded and compared after 30 days of operation under photon exposure. The uncooled device showed significant morphological degradation of the nanorods, including coalescence and surface cracking. In contrast, the cooled device retained structural integrity and exhibited morphological features closely resembling those of the fresh sample. The deterioration in surface morphology observed in the uncooled sample led to a reduction in the absorption coefficient and notable photoluminescence quenching. However, the fan-cooled device maintained a higher level of optical stability. Photovoltaic performance was further evaluated using an AM 1.5 solar simulator. The fresh device, owing to its optimal nanorod geometry and large exposed surface area, exhibited superior light entrapment and photon-to-exciton conversion, resulting in the highest observed photocurrent, power output, efficiency, and fill factor. After a 30-day period of operation, the uncooled device demonstrated a marked decline in efficiency, while the fan-equipped device retained significantly higher performance, reflecting improved optoelectronic stability. In conclusion, the use of a forced air convection cooling system effectively mitigates thermal degradation of ZnO nanorods, thereby preserving both the optical and photovoltaic characteristics of the solar cells. This thermal management approach substantially contributes to enhancing the durability and longevity of nanostructured heterojunction photovoltaic devices.

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Author contributions

All authors contributed to the study conception and design. NN: Methodology, writing— original draft,

investigation, visualization, formal analysis, writing—review and editing, resources, validation. HG: Resources, Formal analysis, writing—original draft, writing—review and editing, validation. HGD: Supervision, validation, resources, writing—review and editing. MK: Visualization, formal analysis. AK: Investigation, writing—review and editing. SMKS: Validation, resources, writing—review and editing. All authors read and approved the final manuscript.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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