

Use of absorber plate built of ZnO/PVC/Bioactivation modified epoxy nanocomposites to improvement of double-effect Solar Distiller productivity analyzing the Energy, Exergo-environment and Enviro-economical

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ABSTRACT

In this study, solar thermal desalination methods were developed to enhance the day to day efficiency of solar distillers by improving their portability and water purification properties. The performance of solar stills is highly contingent on environmental factors, making it essential to address these variables. To achieve this, a double-slope single basin solar distiller (DSBD) was upgraded by incorporating a partially coated absorber plate with ZnO/PVC/Bioactive nanocomposite (ZPBN), which was subsequently examined for its impact on drinking water production from multiple perspectives, including energy, exergy, environmental, and economic considerations. The ZPBN material was synthesized using the solvent casting technique, and its properties were comprehensively characterized through various analytical methods. X-ray diffraction (XRD) analysis revealed a regular crystalline lattice structure amidst an amorphous background, and scanning electron microscopy (SEM) images confirmed its surface performance. The presence of ZnO nanoparticles within the PVC and bioactive matrix imparted enhanced thermal characteristics to the DSBD, including higher temperatures, specific heats, and thermal stability compared to the ZPBN. The study demonstrated that the introduction of ZPBN significantly increased drinking water yield by up to 126% due to its enhanced absorption of solar energy. Furthermore, the energy efficiency of the DSBD improved by 0.44%, while its exergy efficiency decreased by 0.25% when compared to a conventional double slope single basin solar distiller (CDSBD) under the tropical climate conditions of Vijaya-wada, India. In terms of energy matrices, the ZPBN-coated basin area exhibited minimum and maximum energy payback times of 6.55 years and 0.15 years, respectively. Over its lifetime, the DSBD was found to reduce carbon dioxide emissions by 2.97 tonnes and offered the lowest cost per litre, amounting to \$0.0360. The incorporation of ZPBN on the absorber plate within the DSBD resulted in excellent environmental and energy economies, with values of 4.640 kWh/\$ and \$83.210, respectively.

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1. Introduction

Water is the essence of life, and we find ourselves in a challenging and costly era when it comes to ensuring water accessibility. Ashkan and Anders (Nabavi-Pelesaraei and Anders, 2023) used life cycle assessment (LCA) and life cycle costing (LCC) to evaluate two chickpea production systems in Iran: irrigated chickpea production (ICP) and dry farming chickpea production (DFCP). They found that DFCP has a lower environmental impact and cost than ICP. This is because DFCP does not require irrigation, which reduces water consumption and greenhouse gas emissions. Moein et al. (Moosavi-Nezhad et al., 2022) compared the energy use, economic, and environmental impacts of two grafting and acclimatization systems for watermelon seedlings in Iran: conventional tunnel systems (CTS) and LED-equipped vertical systems (LVS). They found that LVS is more sustainable than CTS, with lower energy consumption, environmental impact, and cost. Elham Saeidi et al. (2022) evaluated and optimized the technical and economic efficiency of saffron farms in Iran using two optimization methods: data envelopment analysis (DEA) and multi-objective genetic algorithm (MOGA). Both methods were able to improve the energy efficiency and reduce the production costs of saffron farms. However, MOGA showed better results than DEA in both energy and economic terms. Payam Mohseni et al. (2018), A study combined life cycle assessment (LCA) and data envelopment analysis (DEA) to investigate the energy flow and environmental impacts of grape production in Iran. The study found that 22.41% of the studied vineyards operated efficiently. The coupled application of LCA and DEA showed a reduction in environmental impacts in the range of 0.25% for acidification to 18% for ozone layer depletion. The authors concluded that the results of the study can help to convince farmers to reduce input consumption and achieve operational efficiency, lower costs, and lower environmental impacts.

Solar energy continues to support the needs of the residents of remote areas with easy energy, cheap systems, and clear environment (Panchal et al., 2021a), Mohandass Gandhi et al. (Mohandass Gandhi et al., 2022) investigated the influence of $\text{SiO}_2/\text{TiO}_2$ nanoparticles on the performance of a single slope stepped basin solar still. They found that coating the basin with a mixture of $\text{SiO}_2/\text{TiO}_2$ nanoparticles at a concentration of 30% resulted in the highest efficiency of 40.241%. This is due to the synergistic effect of the nanoparticles, which enhances the thermal conductivity of the system. Mohammad Hatim et al. (2023) conducted an environmental-economic-exergy assessment of safflower production under different tillage systems with Zn and Fe micro-nutrients. The study found that reduced tillage (Sc-RT) was the best scenario from all three perspectives, followed by conventional tillage (Sc-CT) and no-tillage (Sc-NT). The authors recommend that farmers use Sc-RT to reduce environmental impacts, costs, and energy consumption. Kumar et al. (Rajesh Kumar et al., 2022) investigated the use of silicon dioxide nanoparticles (SiO_2 NPs) synthesized using a green method with *Jatropha curcas* L. leaf extract to improve the performance of a single slope solar still. They found that the use of SiO_2 NPs increased the productivity yield of the solar still to 8.79 L/day in summer and 6.49 L/day in winter, compared to the control solar still without SiO_2 NPs. Ashkan et al. (Nabavi Pelesaraei et al., 2023) evaluated three machine learning (ML) methods for predicting the exergoenvironmental damage and emissions social cost (ESC) of mushroom production in Iran. The results showed that the support vector regression (SVR) model was the best performing model, with high accuracy and low error rates. The authors concluded that ML models can be used to provide comprehensive and applicable exergoenvironmental-economical assessments of agricultural products. Davood et al. (Maklavany et al., 2023) applied to five synthesis routes of MIL-53(Fe) production to assess the potential and unintended environmental impacts of life cycle assessment (LCA). They also conclude that route 5 is the most suitable method for producing MIL-53(Fe) owing to its simplicity and the lowest environmental impact and cost. The authors also developed an integrated method of LCA and LCC for the eco-design of MIL-53(Fe), which can be expanded

further to test greener solvents and reuse them in production processes. Yandri et al. (2023) immobilized *A. fumigatus* α -amylase on chitin, which improved the enzyme's stability and reusability. The immobilized enzyme retained over 46% of its initial activity after six consecutive applications for starch hydrolysis, demonstrating the potential of chitin for the production of immobilized enzymes on an industrial scale. Harsito et al. (2022) developed a photovoltaic-thermoelectric generator system that increases power output by 4.2% compared to conventional photovoltaic systems. The system uses a thermoelectric system to convert waste heat from the photovoltaic panel into additional electricity. Arshad et al. (2011) investigated the effects of transparent material in a double exposure solar still with a honeycomb structure. They found that the use of transparent material increased the distillate output to 2.650 l/day and the average efficiency to 39.74%. Shanmugan et al. (2020) investigated the use of a hybrid coating material of TiO_2 and Cr_2O_3 nanoparticles to improve the performance of a single slope solar still. They found that the hybrid coating material increased the water productivity of the solar still to 7.89 L/day in the summer season and 5.39 L/day in the winter season. Bahareh et al. (Hamidinasab et al., 2023) provides a systematic and comprehensive review and critical discussion of the environmental life cycle assessment (LCA) and exergetic analysis of applied solar technologies in the agri-food sector. The photovoltaic systems are the most exergo-environmentally friendly among all solar systems, while the concentrated solar power system exhibits favorable characteristics compared to photovoltaic/thermal (PV/T), particularly from the perspective of LCA. Alsaiani et al. (2022) conducted an extensive investigation to evaluate the impact of combining TiO_2 /jackfruit peel (TJP) with black paint, using various ratios (0.1%, 0.2%, 0.3%), along with the utilization of a nanofluid composed of cobalt (II) chloride, thiourea, and silicon dioxide (CTS) in varying proportions (10%, 20%, 30%, 40%, 50%, and 60%). The experimental analysis was carried out within a single-slope solar still, and they achieved a remarkable daily yield of 8.7919 L per square meter by employing TJP (0.3%) in conjunction with CTS (40%) and silver-colored steel balls. Ravinder Kumar and his team (Kumar et al., 2023) conducted experimental research on a double-slope solar still, utilising TiO_2 nanomaterials blended with Jackfruit peel obtained through a green synthesis process. Their findings indicated that this innovative approach yielded a percentage of energy and exergy capture at 4.71% and 3.35%, respectively. Emad Ismat Ghandourah et al. (Emad Ismat Ghandourah et al., 2022) conducted a study to investigate the impact of incorporating nano LaCoO_3 /mat black paint into the wick materials within a double-slope solar still. It is found to be significantly influenced by the addition of a 20 wt % LaCoO_3 /black paint coating, yielding 5.40 kg/m^2 per day, as opposed to the non-coated version with a daily productivity of 3.85 kg/m^2 per day, both operating at a minimum saline water mass flow rate of 0.05 kg/min . In a thermodynamic analysis conducted by Sangeetha et al. (2022), they examined the performance of a double-slope U-shaped stepped basin solar distiller that incorporated *Mangifera Indica* and *Celostia Argentea* activated carbon nanoparticles impregnated with ZnO nanoparticles. The introduction of carbon atoms into the black paint significantly improved the distiller's efficiency, enabling it to achieve an impressive daily yield of 14.92 L per square meter. Al_2O_3 and $\text{C}_{18}\text{H}_{36}\text{O}_2$ were employed within the basin using a controlled drip mechanism to gradually dispense saline water onto the absorbent materials studied by Shanmugan et al. (2018). The typical efficiency of the solar still was observed at 59.14% during the summer and 27.13% in the winter, resulting in 7.460 kg/m^2 per day during warmer months and 4.120 kg/m^2 per day during colder months for freshwater condensation. Abdullah et al. (2021a) explored the use of copper oxide nanoparticles, Panchal et al. (2021b) investigated the effectiveness of manganese oxide nanoparticles, Sutantyo et al. (2022) investigated the dynamics of DNA in a temperature-controlled environment, considering DNA as a bio-fluid with different viscosities. DNA can be described by wave-like solutions, which fluctuate as the temperature increases and evolve with changes in the perturbation

parameter. For a specific viscosity of bio-fluid, the authors determined the denaturation temperature of DNA to be between $370\text{ K} \leq T \leq 380\text{ K}$. Numerous researchers have examined the performance of solar stills enhanced with nanomaterials and phase change materials. Gandhi et al. (Mohandass Gandhi et al., 2021) utilized $\text{SiO}_2/\text{TiO}_2$ nanolayers, and Hitesh Panchal et al. (2021c) used in Manganese Oxide materials, Abdullah et al. (2022) PCM mixed with CuO nanoparticles, Palanikumar et al. (2019a) conducted an experimental examination of the thermal characteristics of food items using fuzzy logic techniques. In their study, they employed phase change material (PCM) $\text{C}_{18}\text{H}_{36}\text{O}_2$ and nanoparticles (Al_2O_3), both in conjunction with black paint, to analyse the performance of the cooker with and without the application of these coating materials. As a result of the surface coating with nanomaterials, the solar box cooker achieved a temperature of 92°C , and this outcome was statistically validated. Abdullah et al. (2021b) evaluated and corrugated absorber designs for solar distillers. When compared to a typical solar distiller, the distillate from the corrugated tray distiller was improved by 150%. Using computational fluid dynamics, Nader Rahbar et al. (2018) improved two solar stills and demonstrated increased recirculating zone strength and enhanced water output in the tubular still. With redesigned passive solar stills, Pinakeen Patel and Rajesh Kumar (Patel and Kumar, 2016) examined several water depths and improved the thermal performance of the frontal height by between 11.24% and 23%. Sahota et al. (Lovedeep Sahota and Tiwari, 2017) implemented a dual slope solar distiller used with various nanofluids. The model produced thermal performance analysis of energy, exergy, enviroeconomic. Al_2O_3 , TiO_2 , and CuO nanofluids are used by a system. Al_2O_3 , TiO_2 , and CuO were employed to create the nanofluids based on 19.10%, 10.38%, and 5.25% during the system's manufacturing. Al_2O_3 (26.76%), TiO_2 (19.36%), CuO (12.96%) have all increased in energy. Al_2O_3 , TiO_2 , and CuO account for 37.77%, 25.55%, and 11.99% of the system's exergy, respectively. The environmental parameters are $I = 4\%$, 8% , and 10% for the different interest rates of economics.

Balan et al. (2011) conducted a comprehensive review of passive solar stills, which encompassed a detailed exploration of their classification, historical evolution, and the diverse range of designs facilitated gap analysis, aiding researchers in comprehending the evolution of earlier concepts and guiding the development of innovative designs. Palanikumar et al. (2019b) experimentally investigated the thermal image of the food stuff via fuzzy logic methods. They used PCM ($\text{C}_{18}\text{H}_{36}\text{O}_2$) & Nanoparticles (Al_2O_3), mixed with black paint analyzed the cooker performance with and without coating materials. The SBC achieved 92°C due to the surface coating of nanomaterials, proved statistically. Suresh et al. (2019) have studied the nano basin solar still analyzed by fuzzification and defuzzification method. Due to the implementation of the drip efficiency of the solar distiller is ($7.624\text{ kg/m}^2\text{day}$) without drip ($5.254\text{ kg/m}^2\text{day}$) and achieved an overall efficiency of the system is 45%. Bhavani et al. (2019) (Mohseni et al., 2018) have studied the solar box cooker by influence of Al_2O_3 nanoparticle coated in the bar plate of copper and aluminum. They implemented the fuzzy logic rules to predict the cooker thermal act is 15.14% and adeptness of nanoparticles is 7.10%. In prior studies, Shi et al. (2008) developed an epoxy nano-paste by incorporating TiO_2 particles to explore the influence of epoxy resin, coupled with nano-silica modified with glycidoxypopyl triethoxy silane, on mechanical properties. The typical solar still and light weight, black finished, slowly revolving drum have been modified by Lilian Malaeb et al. (Lilian Malaeb et al., 2014), and three various cover geometries have been researched. The conclusion is that cover design measured temperatures and enhanced productivity. This modification resulted in a noteworthy enhancement in Young's modulus, Shi et al. (Shi et al., 2009), signifying improved mechanical performance attributed to the incorporation of nanoparticles into the epoxy matrix system. The treatment of nanoparticles surfaces with silane coupling agents before their addition to the epoxy matrix significantly improved nanoparticles dispersion, Wichmann et al. (2006). The focus was on preparing epoxy nanocomposite using a direct

incorporation approach for thermoset resin. Furthermore, the addition of nano-ZnO and nano- SiO_2 to PVA/xylan composite materials exhibited augmented mechanical strength, increased moisture and oxygen barrier properties, and enhanced surface hydrophobicity. Spectroscopic and X-ray diffraction analyses (XRD) identified hydrogen bond interactions between the nanoparticles, PVA, and xylan, particularly with a 3% concentration of nano-ZnO and nano- SiO_2 in the composite films, Liu et al. (2019). This synergy arose from the combination of two nanomaterials, resulting in superior adhesive capacity compared to individual nanomaterials in epoxy-based coatings.

While limited literature addresses the enhancement of microwave absorption properties of epoxy using ZnO NPs, this study offers insights into the preparation, characterization, and applications of ZnO NPs as microwave-absorbing materials in epoxy composites. The introduction of ZnO/PVC/Bioactive Nanocomposite (ZPBN) aims to enhance the structural, mechanical, and thermal properties of pure PVC/Bioactive due to the unique properties of ZnO NPs, including their small size, large specific area, quantum effects, and strong interfacial interactions. We introduce ZnO/PVC/Bioactive Nanocomposite as an innovative approach to capitalize on the synergistic potential of nanoparticles, which have shown promise in solar absorption applications and can significantly advance solar desalination processes. Consequently, ZPBN holds promise for a wide range of solar coating applications. PVC/Bioactive materials, when combined with appropriate metal oxides like ZnO yield complexes suitable for the development of high-energy-saving materials, Espiard et al. (Ph. et al., 1995).

In line with previous research articles, numerous scientists have explored various approaches to enhance the production of double slope single basin solar distillers (DSBDs). The present study aims to identify the most effective design for a DSBD that achieves optimal performance when combined with an absorber plate partially coated with ZnO/PVC/Bioactive Nanocomposite (ZPBN). To achieve this objective, four different ZPBN ratios (05%, 10%, 15%, and 20%) were formulated and evaluated under identical climatic conditions (KLEF) to determine the optimal design for maximizing performance. The DSBD was instrumental in implementing the ZPBN features, which were subsequently assessed for their impact on freshwater productivity, energy generation, exergy considerations, environmental consequences, and economic aspects. In pursuit of a high-performance DSBD system, researchers analyzed the solar thermal energy consumption associated with optimal ZPBN utilization. Additionally, the DSBD explored the interplay between energy and exergy through an energy matrices analysis encompassing both environmental (enviro-economic) and economic (exergo-economic) dimensions.

2. Methodology

2.1. DSBD use material and approaches

On the inner surface of the basin region in DSBD with ZPBN created a mixture of wettability surfaces using a partially coated absorber plate. Spraying a commercial water based ZPBN coating on 05%, 10%, 15% and 20% of the basin area prepared the region for the ZPBN combined wettability test. The basin area was first cleaned with a precoat that contained a cleanser to clear the glass surface and basin of pollutants in order to ensure that the coating would adhere to the substrate efficient. Following the cleaning procedure, the surface of the basin region was promptly coated to eliminate pollutants. A 30-min drying interval at room temperature followed the application of ZPBN as a coating to control the environment, which in turn controlled the exposure to solar rays. For the duration of application, the substrate was kept at room temperature to ensure the effectiveness of the basin surface treatment. To help with droplet separation and lessen the combining impact at the absorber plate, covering has placed compilation wall for DSBD basin area. The covering shaped outside by means of larger contact angles, facilitating the condensates evacuation. The coated basin was put in

place on the DSBD's front to promote quicker saline water to salt removal. However, the ZPBN material for the reference DSBD is an uncoated sample from the coated basin region. The absorber plate coated previously completed earlier study, [Shatar et al. \(2022\)](#). The GI sheet used to build the basin was 1 m × 1 m in dimension and 1.5 mm thick. The accuracy, range, and uncertainty of DSBD are measured in [Table 1](#).

2.2. ZPBN collecting and reagent materials

The ingredients, High molecular weight polyvinyl chloride (PVC, $(C_2H_3Cl)_n$) powder with K-value of 69–71, tetrahydrofuran are acquired from Madras Scientific Company (Ashok Nagar, Chennai, Tamilnadu, India). GK Industries Cleaning Products Manufacturers, located in Harika Enclave, Guntur, Andhra Pradesh, India, supplied the zinc oxide nanoparticles, aniline monomer in colloidal dispersion (50% in H_2O), usual element magnitude abouts 50 nm (ZnO). None of the chemicals were further purified before usage. The coatings have been applied on substrates made of the aluminium alloy AA6061T6. From Adama India Pvt Ltd. in Hyderabad, Telangana, India, we purchased ammonium persulfate (APS), sodium chloride, tetrahydrofuran, and hydrochloric acid (fuming 37%, Cat. No. 100314). The following items were purchased from Italmatch Chemicals India Pvt Ltd, Hyderabad, Telangana, India (B N Reddy Nagar, Cherlapalli): sodium carbonate monohydrate, methanol, acetonitrile, and formic acid. All the reactants were of an analytical quality and appropriate for the samples. They were gathered and provided by the mango trees in mango fruits on the KLEF campus, which is located at Latitudes: 16° 30' 49.07" N Longitudes: 80° 37' 47.06. The fruits were also grown on the campus in Vijayawada. Mango fruits are hand-separated into pulp, skin, and seed kernel after being chosen, sanitised, and checked for flaws and physiological issues. The fresh mango peels were cut into thin slices and placed in liquid nitrogen before being lyophilized at 50 mPa and 40 °C. A sieve shaker was used to grind and sift freeze-dried materials into powder (0.6 mm), which was then kept in airtight aluminized bags at 30 °C. All studies were performed using these freeze-dried mango peel samples.

2.3. ZPBN preparation

The ZPBN core-shell nanocomposite was made by oxidatively polymerizing aniline monomer in a colloidal dispersion containing ZnO nanoparticles. In this 100 ml water solutions' result that previously contains aniline monomer (0.03 mol), hydrochloric acid (0.03 mol), 8.1408g for ZnO nanoparticles are disseminated with ultrasonic technology. ZnO mixture an aniline monomer was added dropwise to the solution of 0.03 mol Ammonium persulfate as oxidant/initiator while being vigorously stirred in an ice bath. It has been 8 h since the polymerization started. After filtering and washing with distilled water, the nanocomposite of polyaniline and ZnO nanoparticles was examined then dried at 65 °C. Tetrahydrofuran solvent is used to dissolve 0.5 g of PVC concentrate. With 10 ml solution of PVC in mango peel powder, 0.0021 g of ZnO-tetrahydrofuran with mango peels powder nanocomposite was dispersed by ultrasonic for the physique fraction of ZnO-mango peels powder epoxy nanocomposites to PVC is 5:100. ZPBN was

produced as a tetrahydrofuran suspension, Mankomal and Harpreet Kaur ([Mankomal, 2022](#)).

2.4. ZPBN characterizations

As a result, we synthesized the structure in ZPBN and studied it using various methods in our work. We monitor the materials using a variety of techniques, including UV–vis, X-ray diffraction, contact angles, and scanning electron microscopy (SEM).

2.4.1. X-ray diffraction investigations on ZPBN characterization of crystalline

ZnO/PVC powdered mango peels are analyzed using ZPBN materials in XRD patterns ([Fig. 1\(a\)](#)), and after they have been blended, the nanocomposites produced across the 2θ range 10°–70° are displayed ([Fig. 1\(b\)](#)) for the semicrystalline individual abouts ZnO specified with a strong peak at $2\theta = 19.55^\circ$ and 40.04° of pure ZnO in XRD pattern ([Fig. 1\(a\)](#)). According to the form of the crystallisation structure, ZnO is divided into the α , β , γ and δ phases. These results are compatible with values that have previously been reported in the literature, Dillon et al. ([Dillon et al.](#)). Mango peel powder an unstructured character was followed the patterns of XRD views illustrated ([Fig. 1\(a\)](#)), where pure ZPBN for the highest strength, which goes to the α -phase with a pure PVC, was found at 19.9° . ZPB greatly transparent characteris revealed in [Fig. 1\(a\)](#), which also shows several intense peaks for $2 = 31.77^\circ, 36.23^\circ, 47.56^\circ$, and 56.61° . The usual diffraction pattern of ZnO may be matched to some reflections with a ZPB by XRD pattern, which correspond to (100), (002), (101), (102), and (110). ZPBNelement dimensions is determined beginning X-rays diffraction summits using the Debye-Scherrer formula, and it is 55 nm, 45 nm, and 44 nm, individually.

$$D = \frac{0.9(\lambda)}{\cos \theta (\beta)} \quad (1)$$

anywhere X-rays wavelengths have λ (1.58 Å) and Bragg's deflection position has θ , afterwards greatest measurement partially semi limit was β . ZPB blend's points diminished concentrations comparison to various ratios to create mixable intermingling the ZPB occur strans parent level is shown in [Fig. 1\(b\)](#). The intercalation of ZnO particles (0.5%–15%) in the ZPBN blend is confirmed by ZnO-fixed PVC with mango peel nanocomposites patters XRD in [Fig. 2\(b\)](#). The different ratio of In [Fig. 1\(b\)](#), the XRD pattern for 10% and 15% is compared to other peaks, and ZPB is compared to the low intensity peaks. It implies that the crystallinity of the nanocomposites was decreased by the creation of action complexes with the ZPB blend's functional group, [Vickraman et al. \(2009\)](#). They are confirmed the intercalation of nanoparticles within the ZPBN more DSED absorption to produce the more drinking water yield.

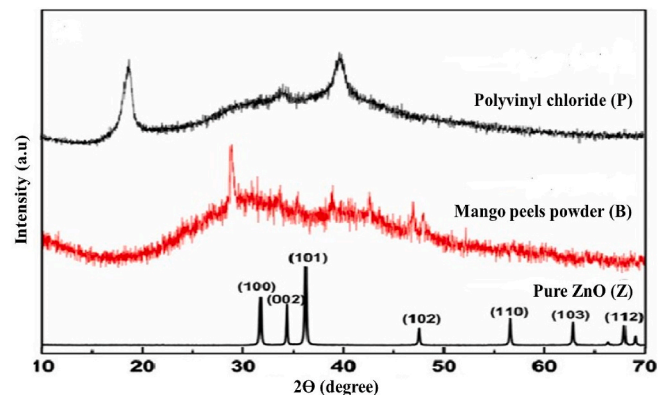


Fig. 1(a). Z, B, P., (elements) analysis of XRD spectra.

Table 1
Shows precision, range, and uncertainty of the DSBD's measuring tools.

S. No	ranges	accuracies	uncertainty	Devices	Units
1	2000 to 00	10 ±	5.7	Solar radiation monitor	W/m ²
2	25 to 00	0.25 ±	0.14	Graduated cylinder	mL
3	105 to 00	0.1 ±	0.058	K – types of thermocouples	°C
4	200 to 00	0.9 ±	0.5	Data logger of temperature	°C

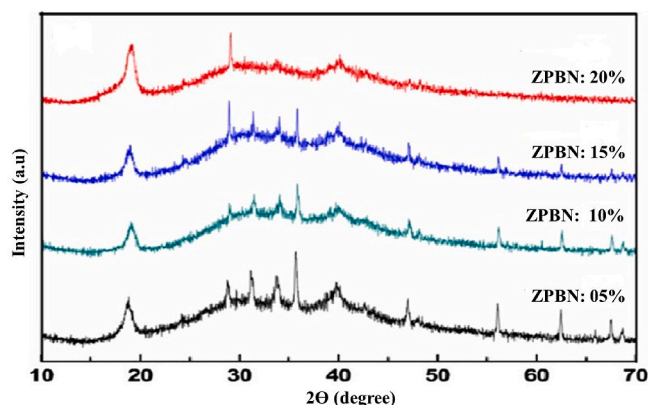


Fig. 1(b). ZPNB examination of various ratios for 05%, 10%, 15%, and 20% loading (wt%) for XRD spectra.

2.4.2. ZPNB analysis of ultraviolet–visible spectroscopy (UV–vis)

To further understand the impact of the ZPNB, optical experiments are described. Optical absorbance spectra in the 200–400 nm range were obtained in Fig. 1(c). ZPNB has been found between 200 and 350 nm in UV area bands with a variety of ratios, absorption intensities, and wavelengths. ZPNB found at nearly 250 nm may be attributed to an absorption band involving bonding. ZPNB the difference in optical band gap is 4.99 and 5.03 eV values for varied loadings. For the ZPNB computed optical band gaps, including direct and indirect. However, when ZPNB (05%, 10%, 15%, or 20%) is added, direct optical band gap shifts as of 04.980–05.020eV while indirect optical band gap shifts as of 04.940–05.090eV. The optical band gap also narrows with 5% ZPNB loading, Linda et al. (2016). The variation explains why the optical band gap as ZPNB quantity disarray is inversely related. This characterisation thus assists in identifying characteristics when communicate band gap absorption material by employing the modified mixture of ZnO and PVC as mango peels.

2.4.3. Scanning electron microscopy (SEM) examination of ZPNBs

An evaluation of the microstructure and surface morphology can be done effectively with the use of SEM. Fig. 2(i, a, b, c, d) displays the chemical blended with various ZPB ratios (05%, 10%, 15%, and 20%). Combining both tiny and large ZPNB pores, 05% of the polymer with mango peels interactions are highly disordered and proper cross linking between Fig. 2(a) depicts the tortuous and meandering course taken by ZPB. Additionally, the SEM microstructure significantly changes when (%) ZnO nanoparticles are introduced to the PB as seen in Fig. 2(b, c, d) from the SEM microstructure of ZPNB (10%). In polymer interaction, mango peels have numerous pores that are virtually spherically shaped and few extremely small sizes. According to Fig. 2(c), the number of pores rises as ZnO nanoparticle loading increases. It has been noted that as the proportion of ZnO nanoparticles in the nanocomposites of

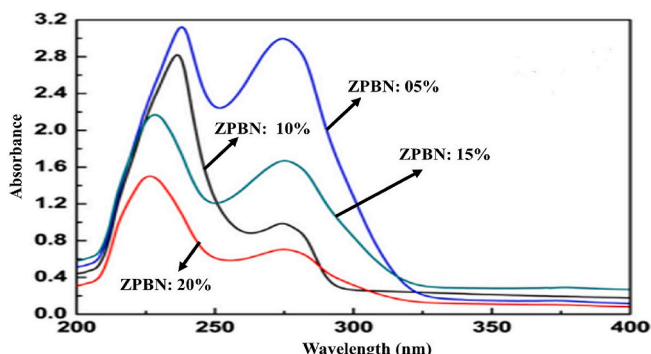


Fig. 1(c). Different ratio for ZPNB analysis of UV–visible spectra.

polymer and mango peels rises, more tiny pores begin to combine the polymer and mango peel contacts. The diameter of the ZPB is initially determined from an instrument for the different ratios (10%, 15%, and 20%) loading of ZnO nanoparticles with PVC by mango peels, it is resulting in a significant for the same scale, the number of tiny pores inside them. A smooth and organised arrangement of small and big pores is created inside the structure with a 15% ZnO nanoparticle loading, but small pores are absent from the SEM morphology. With a 05% ZnO nanoparticle loading, the polymer containing mango peels becomes more porous and has uniformly spaced pores, boosting connection and raising ionic conductivity, Sharma et al. (2008).

2.5. Evaluation of contact angle measurements by ZPNB

ZPNB's hydrophobic qualities were thoroughly investigated quantitatively using contact angle measurements. The degree of hydrophobicity of the epoxy nano-composites increases with contact angle, Cassie et al. (Cassie and Baxter, 1944). Fig. 2(ii) shows that the contact angle decreased hourly from 108.0° to 102.70° and 87.10° as the concentration of ZnO rose from 0 to 2 and 4 h. This decrease in contact angle is brought on by the previously discussed interaction of ZnO nanoparticles with the water molecule. With an increase in ZnO concentration, there are more ZnO nanoparticles on the PVC disc's surface, which improves hydrophobicity. As the concentration of ZnO/PVC/mango peels (ZPB) increases (05%, 10%, 15%, and 20%) to 6hr, the contact angle slightly decreases from the 4hr sample of 108.0°–106.00°, which is consistent with the STRI categorization shifting towards more hydrophobic. As the nanoparticles distance reduces as a result of the higher concentration, agglomeration is caused by increased attraction by the van der Waals forces. The increase in contact angle is explained by the fact that agglomeration cannot be completely avoided at higher concentrations, Alsathy et al. (2018).

2.6. Experimental site and DSED setup

The solar stills under investigation were meticulously designed, assembled, and subjected to testing at the Solar Research Laboratory, located within the Physics Department of KLEF University in Vijayawada, India (16.50° N, 80.64° E). The study period encompassed both summer and winter seasons, spanning from April 2022 to April 2023. Weather data during this period was closely monitored and calibrated based on the performance of the DSBD. Each DSBD unit featured a basin with dimensions measuring 1 × 1 m². The construction of DSBD involved the use of 1.5 mm thick galvanized iron sheets. Notably, a specific angle of 13° was incorporated into the design of the glass cover. This angle was chosen to minimize any potential leakage by compensating for deviations in the glass cover's inclination. A 4 mm thick glass cover was used to further mitigate the impact of any potential leakage, and the angle of inclination was selected based on practical considerations rather than ideal incline angles due to spatial constraints.

The experimental trials with DSBD were carried out within the time frame of 9 a.m. to 5 p.m., with the process of saline water heat distillation commencing at 9.30 a.m. each day. To maximize solar energy absorption, the DSBD units were strategically oriented with their faces directed towards the south. Before initiating each experimental run, saline water with a salinity level of 3.50% was carefully poured into the basin to a depth of 1 cm. Following the completion of each trial, the saline water within the absorber plate was drained, and the basin was thoroughly cleaned in preparation for subsequent experiments. Temperature measurements during these trials were recorded using K-type thermocouples, which were employed to gauge and document the temperatures of various elements including the saline water, absorber plate, glass cover, and the surrounding moist air.

The experimental setup employed in this study involved the utilization of specialized instrumentation to collect essential data. To monitor open-air weather conditions and solar energy, we employed a

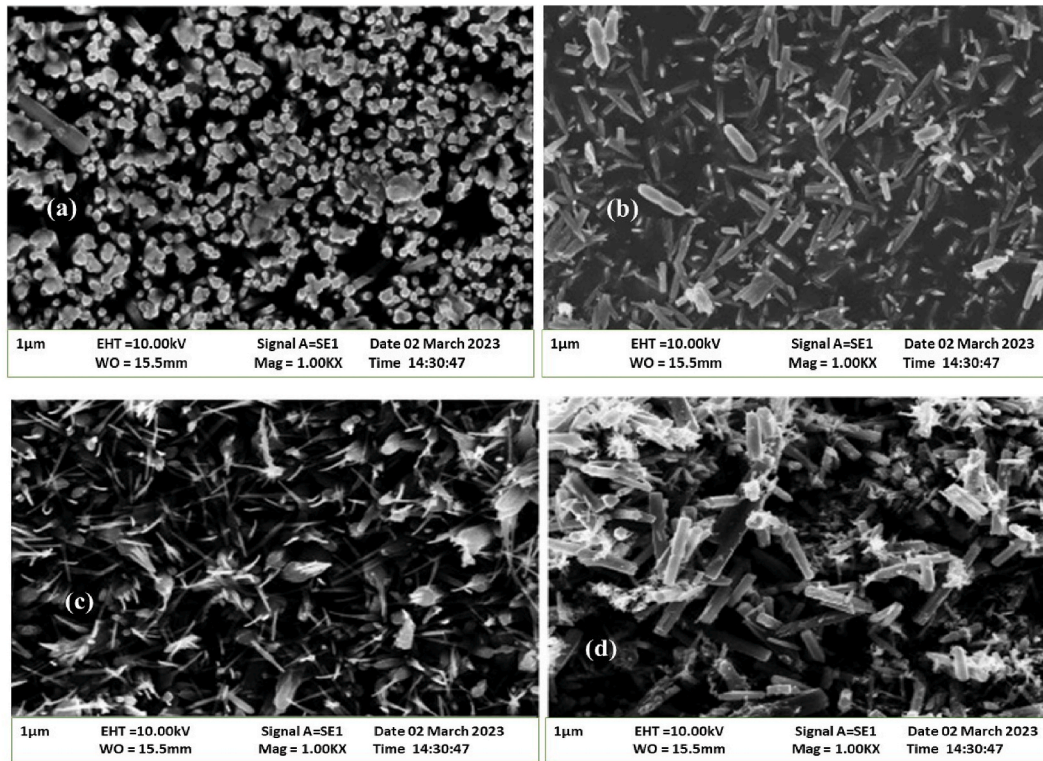


Fig. 2 (i). ZPBN analysis of SEM micrographs at loading weight percentages of 05% (a), 10% (b), 15% (c), and 20% (d).

temperature sensor (Benetech 3016) and a solar power meter (TES-132). The arrangement of this experimental setup is elucidated in Fig. 3(a), while a visual representation of the investigative arrangement is presented in Fig. 3(b). The core of this experimental work consisted of two key components: the DSBD and the ZPBN. In the construction of the DSBD, locally available materials were judiciously utilized to craft a functional unit with specific dimensions. The incorporation of ZPBN and an absorber plate contributed to increased heat generation, subsequently enhancing the yield of the solar distillation process. For detailed information regarding the range, accuracy, and standard uncertainty of the instruments and sensors utilized, please refers to Table 1.

2.7. Economic analysis of DSBD (background theoretical)

Three components are essential an Economics investigation: (i) assessment of the cost of producing drinking water, (ii) relation of value price, (iii) exergo-economic, enviro-economic studies of DSED. The capital budgetgeneratingdrinking water exergo-economic outcomes of the DSED are considered as key factors. As a result of the environmental economic analysis of carbon credits have also been acquired through the estimation of CO₂ mitigation that depends on the interest rate over the DSED lifetime.

2.7.1. DSED used ZPBN for energy productivity

The ZPBN performance may be evaluated using a DSED energy efficiency by using the DSED's energy efficiency is calculated using its input and output energy as following in law of thermodynamics. An output energy can be calculated using the evaporation energy ($m_w \times h_{fg}$), solar power entering the DSED can be used to calculate input energy ($(t) \times A$), where.

"A" denotes the area on which solar radiation $I(t)$ is falling denotes the amount of solar radiation falling on DSED walls each hour, and " m_w " is the mass of water that has been condensed and collected from the solar still. $I(t)$ can be thought of as 2325 kJ/kg of water's latent heat of vaporisation.

Energy efficiency in real-time (η_i) can be expressed as

$$\eta_i = \frac{m_w \times h_{fg}}{\Sigma[I(t) \times A] \times 3600} \quad (2)$$

Additionally, energy efficiency can be expressed as

$$\eta_d = \frac{\Sigma m_w \times h_{fg}}{\Sigma[I(t) \times A] \times 3600} \quad (3)$$

2.7.2. DSED used ZPBN for exergy productivity

The ratio of output exergy measured in terms of water evaporated to input exergy measured in terms of input solar radiation is known as exergy efficiency and is represented by Abd Elbar and Hassan (Abd Elbar and Hassan, 2019) and Hassan (2019).

$$\eta_x = \frac{\text{Exergy out}}{\text{Exergy in}} \quad (4)$$

$$\eta_x = \frac{E_{x, \text{evap.}}}{E_{x, \text{inputs}}}$$

The condensed water dewdrop obvious tilted glass cover to absorber plate, performance of the practical sample it may be lesser than that of hypothetical samples as per day an exergy is determined using Sharshir et al. (2017).

$$E_{x, \text{output}} = E_{x, \text{evap.}} = \frac{m_w \times h_{fg} \times \left(1 - \frac{T_a}{T_w}\right)}{3600} \quad (5)$$

T_a (ambient temperature) and T_w (water temperature) are the values. The exergy input to DSED due to radiation can be characterised as a function of radiation exergy, according to the Petela (2003) model.

$$E_{x, \text{input}} = A_s \times I(t) \left[1 - \frac{4}{3} \times \left(\frac{T_a}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a}{T_s}\right)^4 \right] \quad (6)$$

where A_s represents the total basin area in m², and T_s represents the

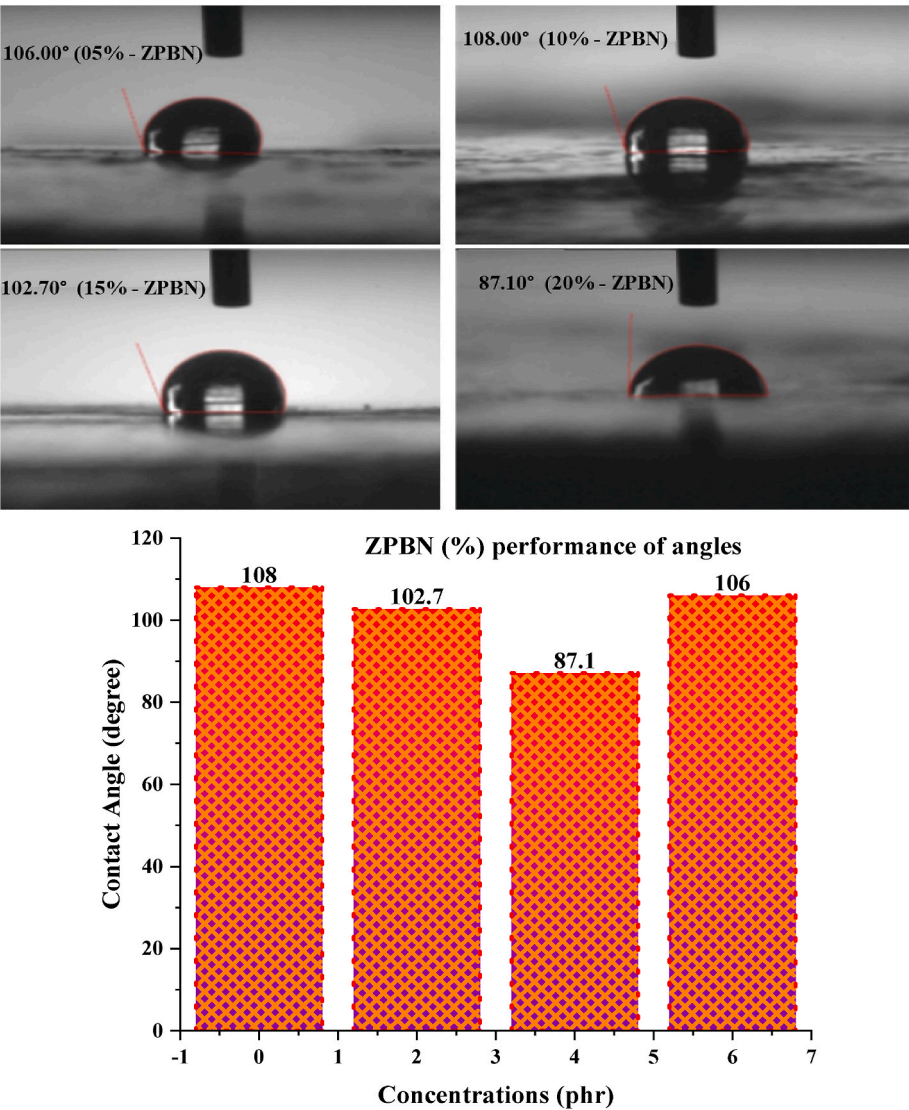


Fig. 2(ii). Contact angle measurements conducted for various ratios of ZPBN blends, specifically (a) 05%, (b) 10%, (c) 15%, and (d) 20%, in conjunction with thermoplastic starch concentrations.

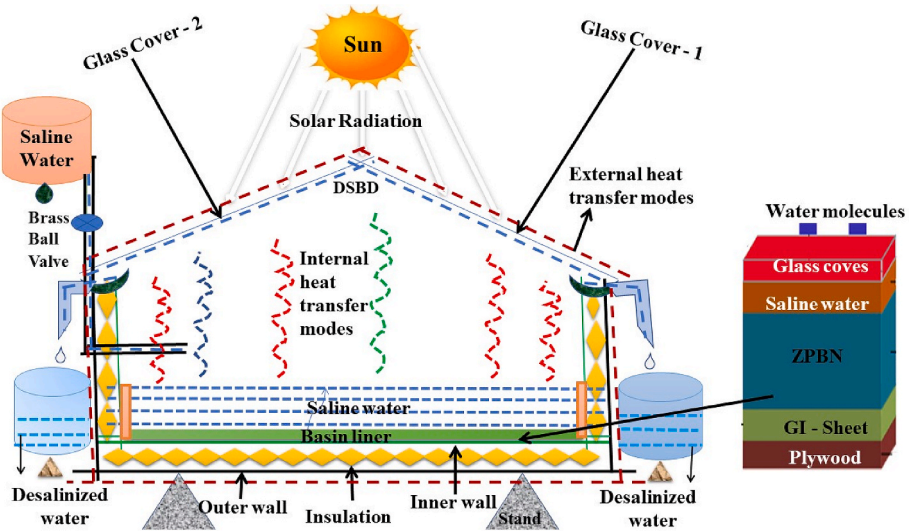


Fig. 3(a). Schematic diagram of DSBD.



Fig. 3(b). Experimental analysis of DSBD.

sun's surface temperature in Kelvins (6000K).

2.7.3. Cost analysis for DSED water production

It's crucial to keep in mind that one of the DSED's top priorities is to reduce the cost of producing one liter of water. Therefore completing an analysis of the costs involved in doing so is necessary. The Capital Recovery Factor (CRF) in DSED was calculated using sequence of equal annual cash payments' current worth. These payments are frequently thought of as annual, and a parameter has been used to analyse effectual expenses, indicating the achievement of an investment over the lifetime of a solar still (n), and it is determined using the formula provided in Nursyahirah et al. (Shatar et al., 2023):

$$CRF = \frac{i \cdot (1 + i)^n}{(1 + i)^n - 1} \quad (7)$$

anywhere "i" is annual bank interests rates and where it is displayed and often checked. Effectual yearly interests' rates, which an alternative to the interest rate belongings compound times have occupied keen on report, it is actual return on savings accounts or any other interest-paying assets displays precise % rates of attention all outstanding debts, including loans. The following connection is used to compute the effective yearly interest rate:

$$AFC = CRF \times C \quad (8)$$

anywhere number compound periods (t), interest rates (i), and effective interest rate (ie) are presented, C is cost of DSBD materials correspondingly. Furthermore, the general compound interest formula's mathematical limit, where interest is compounded annually an infinite number of times is the continuous compounding interest rate.

3. DSBD used ZPBN analysis of exergo-economic and enviroeconomic

Exergo-economic and enviroeconomic can be used in many different fields. The performance of ZPBN materials is regarded as one of thermodynamic studies by integrating exergy, economic analysis, and exergo-economic parameters have been frequently used with a DSBD in recent years. They view the instrument as enabling the collection of data that is not possible through standard energy, exergy, and economic assessments. It is crucial for DSBD and using a cost-effective solution.

3.1. DSBD analysis of exergo-economic studies

The cost-effective analysis of DSBD is supplied to combination of energy and economic analyses of exergo-economic characteristics uniform that equal annual cost and output of energy per year gained with the following relationship:

$$R_{Ex} = \frac{(E_{ex})_{out}}{UAC}$$

$$R_{En} = \frac{(E_{en})_{out}}{UAC} \quad (9)$$

UAC, R_{En} , and R_{Ex} were energy, exergy-based exergo-economics parameter, consistent yearly price calculate annually production exergy $(E_{ex})_{out}$, energy $(E_{en})_{out}$ of DSBD have been found via the resulting equation, Tuly et al. (2022):

$$(E_{en})_{out} = \frac{M \times h_{fg}}{3600}$$

$$(E_{ex})_{out} = \frac{M \times h_{fg}}{3600} \left(1 - \frac{T_a}{T_w} \right) \quad (10)$$

where, the saline water is T_w then ambient temperature is T_a .

3.2. Environmental cost analysis

DSBD employing a ZPBN defined with two environmental and economic criteria, emissions of carbon dioxide and their reduction.

3.3. Emission of carbon dioxide

Inadequate equipment causes distribution loss (40%) and gearbox loss (20%), which together account for around 0.96 kg per kWh of CO_2 generation. Baomin Dai et al. (2022) and 40% of CO_2 reduction, respectively. It is distributed with a value equal to 2 kg per kWh. Additionally, this estimate is based on the average CO_2 equivalent used to produce one unit of energy from fossil fuels, which is used to calculate the annual CO_2 emission. The following outcomes are determined as a CO_2 emission during the DSED lifespan:

$$ACDE = \frac{2 \times E_{in}}{n} \quad (11)$$

$$LCDE = 2 \times E_{in}$$

According to the lifetime CO_2 emission and annual CO_2 emission, the following are E_{in} , ACDE, and LCDE diagrams that show the represented energy to product components of the DSBD.

3.3.1. Energy-based reduction of carbon dioxide by DSED

The DSED's rate of CO_2 reduction in kilogrammes per year has been calculated by dividing CO_2 mitigation over the lifetime of the device by $(E_{en})_{out} \times 2 \times n$ and $(E_{en})_{out} \times 2$. The CO_2 mitigation is made to consider the CO_2 emission across the DSED lifetime when the DSED is used in a net value analysis of CO_2 mitigation per tonne with lifetime:

$$\phi_{CO_2} = \frac{2((E_{en})_{out} \times n - E_{in})}{1000} \quad (12)$$

where the environmental parameters are ϕ_{CO_2}

3.4. DSBD used ZPBN analysis of Enviro-economic studies

By utilising a lifespan equal ZPBN to analyse the enviroeconomic parameter as the following relation calculated the enviroeconomic parameter, the cost of CO_2 reduction during the DSBD is determined as

$$Z_{DZCO_2} = \phi_{DZCO_2} \times X_{CO_2} \quad (13)$$

where DSBD using a ZPBN analysis of Z_{DZCO_2} showed that parameter of an enviroeconomic then international carbon cost is showed of X_{CO_2} .

3.5. DSBD used ZPBN analysis of Exergo-environmental studies

By the moderate degree of contamination method that the energy foundation pollutes the environment, the production of drinking water from renewable sources is very significant. Utilising energy from fossil fuels is necessary for water innovation. Exergo-environmental parameters are examined in DSBD using a ZPBN analysis of CO₂ based on the exergy generated by the parameters, which results in a drop in the exergo-environmental, [Dubey et al. \(2021\)](#) solution.

$$\phi_{DZex, CO_2} = \frac{2(E_{DZex, out} \times n - E_{in})}{1000} \quad (14)$$

In order to achieve the whole CO₂ mitigation of a DSBD utilising a ZPBN, the following steps must be taken:

$$\text{Total CO}_2 \text{ mitigation} = \phi_{ex, CO_2} + \phi_{CO_2} \quad (15)$$

3.6. DSBD used ZPBN analysis of exergo-enviroeconomic studies

Exergy-based exergo-enviroeconomic parameter for the cost of CO₂ mitigation has been evaluated by DSBD using ZPBN analysis of the equation derived using the following as

$$Z_{DZex, CO_2} = \phi_{DZex, CO_2} \times X_{CO_2} \quad (16)$$

where DSBD using ZPBN analysis of Z_{ex, CO_2} has formed that parameter as an Exergo-enviro-economic process.

4. Result and discussions

The DSBD investigates the impact of changing the operational ZPBN temperature (05%, 10%, 15%, 20%) on the freshwater output over the winter and summer, both hourly and daily. Both in the winter and summer, the trials take place across a number of days. In four scenarios with temperatures of 05%, 10%, 15%, and 20%, the effectiveness of employing ZPBN with and without the modified DSBD to control and stabilise the required absorber plate temperature is evaluated for the product contrasted with conventional solar distiller (CDSBD) functioning similar weather circumstances with identical proposal still settings throughout the winter or summer.

4.1. Analysis of temperatures in DSBD (glass cover, salinity water, absorber plate)

[Fig. 4\(a\)](#) and [Fig. 4\(b\)](#) depict air temperatures and solar radiation that were measured throughout the experimental working days.

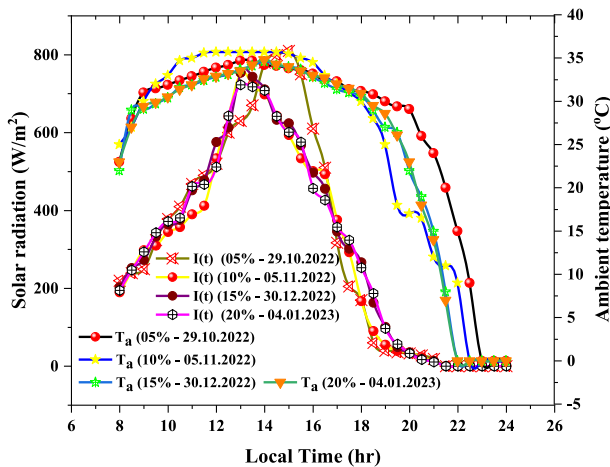


Fig. 4(a). ZPBN winter performance assessed using experiment involving $I(t)$ and T_a .

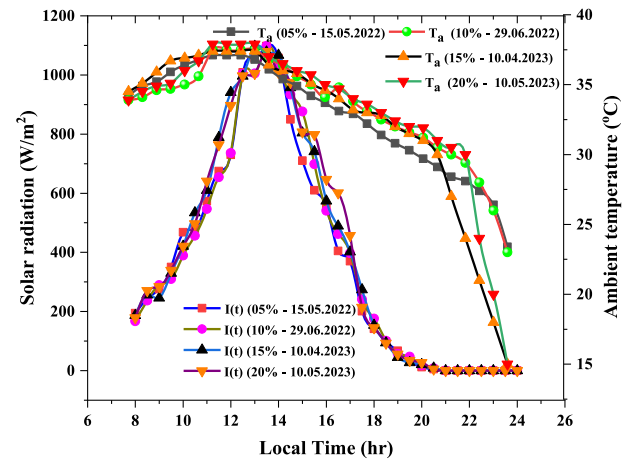


Fig. 4(b). ZPBN summer performance assessed using experiment involving $I(t)$ and T_a .

Normally, India witnessed drier weather and a lot of solar radiation from 05 May 2022 to 05 May 2023, when the KLEF was held in Vijayawada, India. However, the weather in Bezawada, a city in eastern-central Andhra Pradesh state in southern India, changed due to the Krishna river phenomenon, causing heavier-than-usual rain, overcast skies, and generally cooler weather in July to September 2022 compared to earlier years (World Meteorological Organisation, 2022). The inconsistent Solar radiation ($I(t)$) that was guaranteed during the experimental working days demonstrated this effect of DSBD. Nevertheless, ambient temperature (T_a) demonstrated a comparable pattern for the winter and summer working days, with a modest decline from 8.00am to 12.01am (midnight). In ZPBN performance of 05%, 10%, 15%, and 20%, different days, the average $I(t)$ and T_a have been measured at around 317.94 W/m² and 27.05 °C (Winter) and 387.38W/m² and 35.15 °C (Summer), individually. Average glass cover temperature (T_g), basin temperature (ZPBN), T_b , and salinity of the water (T_w), Temperature of moist air (T_m) for [Fig. 4\(c\)](#) and (d) depict the DSBD in summer and winter days. The performance of ZnO nanoparticles was incorporated into a PVC/bioactive matrix to improve the transparency and solar energy absorption of the films. The UV-visible spectra showed that the transmittance intensity increased with increasing wavelength and ZnO nanoparticle concentration. The solar energy absorption of the films also increased with increasing ZnO nanoparticle concentration. The films were

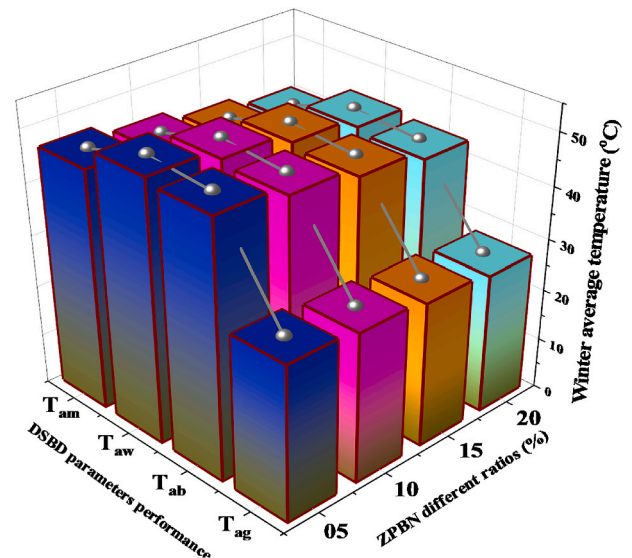


Fig. 4(c). Winter average temperature of DSBD using ZPBN (%) performance.

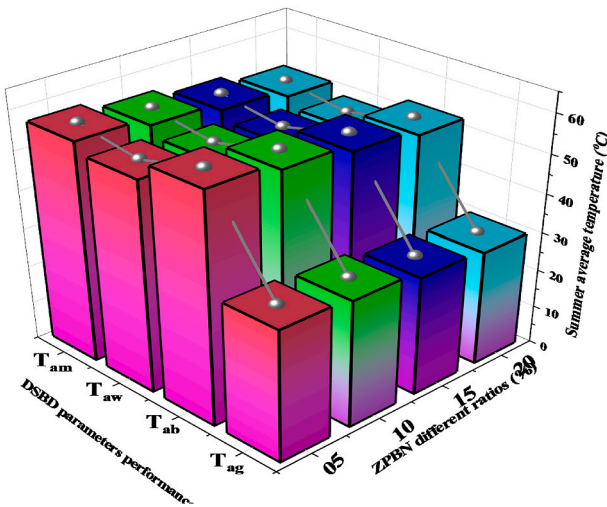


Fig. 4(d). Summer average temperature of DSBD using ZPBN (%) performance.

subjected to solar energy during the day, which caused them to vibrate and generate heat. The defects in the films were gradually reduced in the evening. This reduction in defects decreased the density of localized states in the band structure, which increased the transparency of the films. The UV-visible spectra were analyzed to determine the different ratios of ZnO nanoparticles in the films.

The DSBD's highest basin temperatures (T_b) for the glass cover (T_g), saline water (T_w), and moist air (T_m) on various days (winter) were, respectively, 68.5 °C, 43.01 °C, 68.5 °C, and 71.5 °C, depending on varied ratios of ZPBN (05%, 10%, 15%, and 20%) coated on absorber plate. The average greatest T_g , T_m , T_b , and T_w values for the DSBD were 28.75 °C, 47.51 °C, 46.55 °C, and 43.58 °C, on a scale of 05%, whereas the values for the ZPBN coated with absorber plate values were 6 °C (winter) higher than another ZPBN contraction ratios of the solar still (Winter). Similar to the summer also employed the various ZPBN ratios by utilising T_g , T_m , T_b , and T_w on various summer days, which are 46.45 °C, 83.32 °C, 79.02 °C, and 77.75 °C, respectively, and are higher than the 05% by 14 °C. The findings demonstrated that ZPBN utilising various ratios in the winter and summer had lower than 10% for all mechanisms. Using absorber plates in DSBD, 15%, 20% were lowered by 5 °C, 4 °C and dropped to 3 °C. T_b increased for the ZPBN coated absorber plate DSBD compared to the 10%, 15%, and 20% when the absorber plate of thermal energy storage was heated from 75 °C, 73 °C and 72 °C. T_b of coated absorber did not decrease with greater temperature, in contrast to earlier investigations on absorber plate. Temperature increase attributed greater speed evaporation, more heat energy from condensation (latent heat) was absorbed by glass cover, increasing T_b made worse by the addition of coating (10%, 15%, and 20%), which increased the absorber's thermal resistance and impeded the inner basin area's ability to dissipate heat into the saline water. Nevertheless, as DSBD increased, the gap between T_g and T_w widened, and this had an impact on how quickly production increased. The significance of ZPBN coatings on DSBDs were investigated for their solar energy absorption, internal heat transfer, and thermal energy performance. It was found that the addition of ZnO nanoparticles to the ZPBN coatings increased their solar energy absorption and internal heat transfer, which improved the thermal energy performance of the DSBDs. This is because the heat energy encourages fusion at the contact points between basin to glass cover, providing a strengthening effect. Additionally, the heat energy improves the distribution of ZnO nanoparticles in the ZPBN coating, which further increases the heat energy absorption of the coating. The results suggest that ZPBN coatings with ZnO nanoparticles are promising for improving the thermal energy performance of DSBDs.

4.2. DSBD production of freshwater

On all the experiment days utilised with and without ZPBN (05%, 10%, 15%, 20%), the freshwater higher of 05% was conducted an hour earlier than the 10%, 15%, and 20% in Fig. 5(a) (Winter), Fig. 5(b) (Summer) of total yield DSED that have been created. With ZPBD ratios of 05%, 10%, 15%, and 20% with a maximum hourly highest yield for DSED of 0.413, 0.371, 0.249, 0.236, kg/m²h and 0.117 kg/m²h without ZPBN, and 0.336, 0.331, 0.329, 0.316 kg/m²h and 0.107 kg/m²h without ZPBN, respectively, in the summer and winter. While the greatest average hourly production for DSED employing coated absorber plate with ZPBD various ratios is 0.143 and 0.196 kg/m²h for 05% in the winter and summer, respectively. For coated ZPBD with a ratio of 05%, an even more dramatic rise in hourly yield per day of 6.4812 (05%), 5.764 (10%), 4.341 (15%), 3.953 (20%), kg/m² per day and 2.213 kg/m² per day (WtZPBN) and 4.931 (05%), 4.785 (10%), 4.453 (15%), 4.295 (20%), kg/m² per day and 2.106 kg/m² per day (WtZPBN) was discovered on summer and winter, the cumulative yield for the DSED, respectively. When compared to the 10%, 15%, and 20% ratios in a system, increasing the ZPBD proved to enhance the yield of the coated absorber plate DSED by 51% (summer) and 32% (winter). This observation is indicative of the enhanced transparency of ZPBN films upon the incorporation of ZnO nanoparticles into the PVC/Bioactive matrix. Additionally, the transmittance intensity across all samples is seen to rise with increased (summer and winter) solar energy absorption in the basin internal mode progress.

4.3. ZPBN coated in DSBD efficiency

The nano-indentation technique was used to evaluate of ZPBN coatings on DSBD results showed able to smoothly bear different loads without cracking, suggesting that they had good absorption to the DSBD substrate. The addition of ZnO nanoparticles to the ZPBN coatings increased their load-bearing capacity, except for the 15% coating, which did not contain ZnO nanoparticles. From Fig. 5(c) and Fig. 5(d) depict per day energy and exergy efficiency with coated, uncoated ZPBN in DSBD efficiencies. Depending on the day of the experiment, uncoated ZPBN in DSBD has varying energy efficiency with the highest efficiency being 32.7% in the summer and 28.7% in the winter for 05%. The variation in the DSBD's energy efficiency was caused by different ratios (10%, 15%, and 20%) in the freshwater productivity of 28.2%, 23.9%, and 21.7%, and without coated ZPBN, which is 16.3%. The solar radiation measured on the test days in summer and winter was 27.8% (10%), 24.7% (15%), 23.6% (20%), and 14.8%, respectively, without coated ZPBN. In contrast to the DSBD, the coated ZPBN absorber plate with

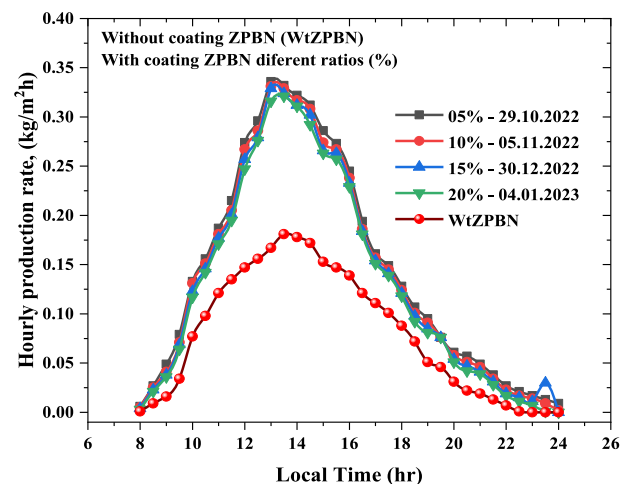


Fig. 5(a). ZPBN coated for the hourly production of DSBD freshwater in winter days.

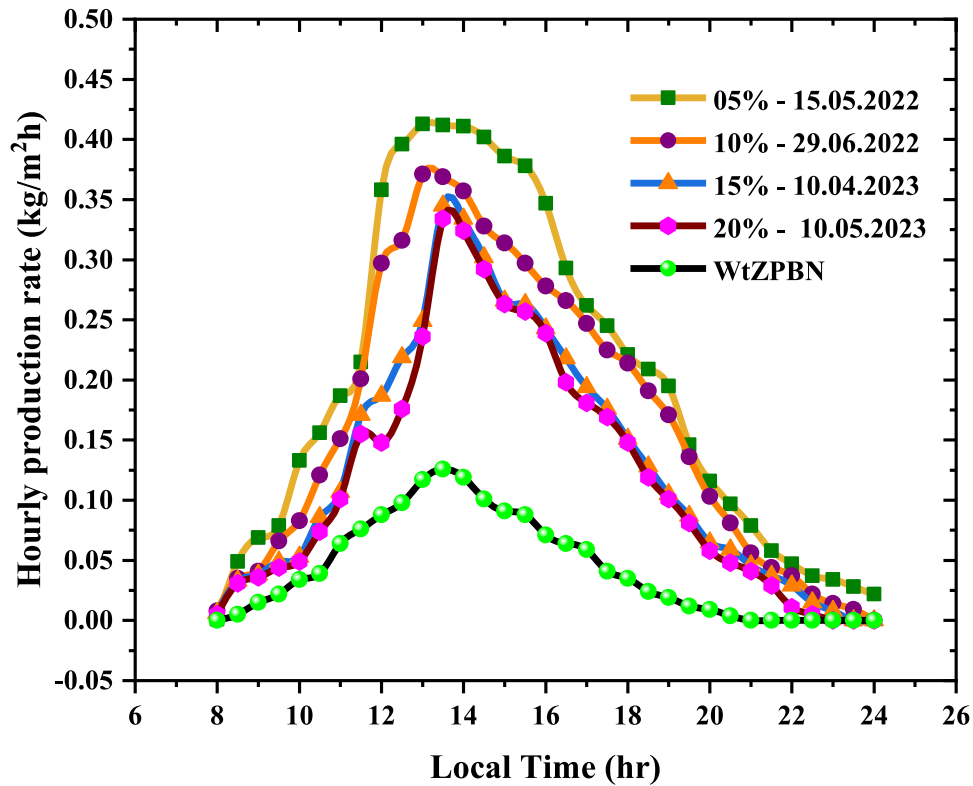


Fig. 5(b). ZPBN coated for the hourly production of DSBD freshwater in summer days.

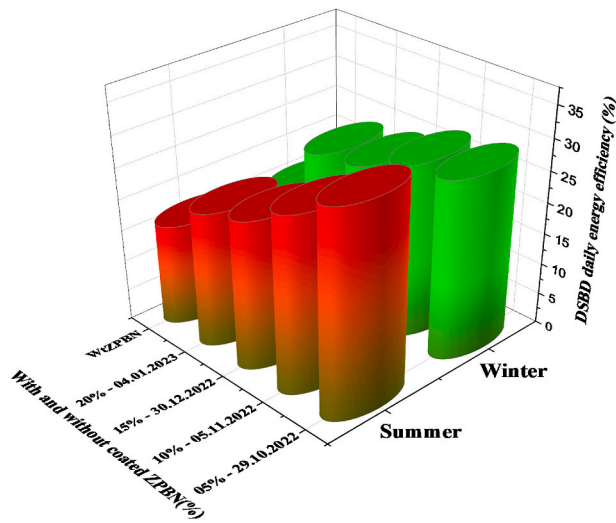


Fig. 5(c). DSBD energy efficiency coated in ZPBN at different ratios in summer days.

summer days and winter days had the maximum efficiency of 16.4%, which was followed by 14.1% for 05% in Fig. 5(c).

4.4. ZPBN coated in DSBD energy matrices and CO₂ emission

On the days of the summer and winter experiments, Table 2 displays energy payback time (EPBT); energy production factor (EPF) in DSBD. This table's reference to the total embodied energy comes from Table 2 measurement. More than twice as much energy is embodied in a DSBD when coated materials are used for the reducing CO₂ emissions. The amount of CO₂ released and reduced for reference and coated ZPBN with absorber plate in DSBD is shown in Table 3. The solar still with an

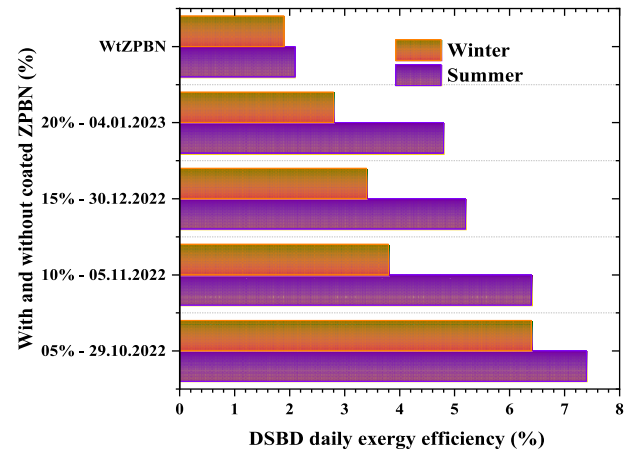


Fig. 5(d). DSBD exergy efficiency coated in ZPBN at different ratios in winter day's.

Table 2

Energetic and exergetic shows energy payback time (EPBT), energy production factor (EPF) on DSBD.

For Parameters, DSBD	Summer	Coating ZPBN	Winter	DSBD
Energy contained (kWh)	141.12	343.56	144.32	425.51
Annual yield (L/m ²)	195.64	292.00	170.09	383.98
E _{out} , annual (kWh)	32.38	48.22	28.15	63.36
E _{xout} , annual (kWh)	11.87	13.47	15.19	18.17
EPBT _{en}	4.25	6.98	4.89	6.55
EPBT _{ex}	11.59	24.98	9.06	22.83
EPF _{en}	0.24	0.14	0.20	0.15
EPF _{ex}	0.09	0.04	0.11	0.04

Table 3
CO₂ emissions and climate change adaptation in DSBD.

Parameter	Summer	Coated ZPBN	winter	DSBD act
Energy contained (kWh)	141.12	343.56	144.32	425.51
CO ₂ lifetime emissions, in tonnes	264.351	598.53	321.26	789.42
Annual yield (L/m ²)	195.64	292.00	170.09	383.98
E _{out} , annual (kWh)	32.38	48.22	28.15	63.36
Ex _{out} , (kWh) yearly	12.67	21.35	22.36	21.21
Mitigates CO _{2ex} , lifetime (CO ₂ tones)	2.53	3.34	2.36	3.76
lifespan (tones CO ₂) mitigated CO _{2 ex} .	0.56	0.23	0.56	0.31

absorber system produced three times as much CO₂ throughout its 30-year lifetime as the DSBD.

4.5. Distilled water per litre cost, exergo and enviro-economic analysis

The prices of the materials needed to construct the solar still are shown in Table 4. ZPBN and DSBD have capital costs of \$ 1480 and \$ 232.60, correspondingly. An economics with parameters designed as current analysis listed in Table 5. DSBD utilising coated ZPBN has an overall annual cost of \$08.680 and \$13.640, correspondingly. DSBD (CPL) employing covered ZPBN for the various testing days (winter and summer) is shown in Table 6. The exergo-economic and environmental costs of the DSBD and coated ZPBN (0%) are contrasted in Table 7. According to Ren's exergo-economic analysis based on energy, the addition ZPBN (05%) boosted outcome by 43% in comparison to other materials (%). Rex for coated ZPBN with absorber plate in DSBD has a lower exergo-economic analysis based on exergy than another ZPBN, which has a lower exergy of \$83.21. Current study to comparison prior an employing the ZPBN system has been investigated parameters shown in Table 8. Due to the size and materials utilized to construct the DSBD, the embodied energy for the current study was cut in half compared to the prior study. The annual yield produced was comparable to that of the prior study, however the system's energy output was much less than that of the prior study employing ZPBN. As a result, the parameters computed using energy output were worse than in the earlier study. The system performed improved parameters determined conditions an exergy compare to earlier swot, despite exergy output being lower than previous study as well. The values of CPL has around seven epoch inferior than that of the prior solar distiller, the current DSBD proved a supplementary gainful when compare an earlier studies.

4.5.1. Experiments and data collection

The experiments involving the ZPBN-coated absorber plate within the DSBD units were meticulously conducted to evaluate their performance across both summer and winter seasons. The analysis focused on key efficiency parameters, including energy efficiency and exergy efficiency, and compared DSBD units with and without ZPBN coatings.

Table 4
Cost of components utilized in the DSBD.

Entry	(\$.) Cost
Sheet of GI (Basin)	69.9
Glass coating	39.2
Cover of glasses	39.9
Foam of PE	12.1
Set of ZPB	69.2
Sourcing DC control	11.2
Pump of DC.	5.2
Service of fabrication	31.1
whole (DSBD)	151.1
whole (ZPBN coated)	222.5

Table 5
Total annual cost (TAC) in DSBD benefits ZPBN performance.

Materials Cost analysis	DSBD	ZPBN acts
Cost of capital, C (\$)	151.21	331.51
Factory for capital recovery, CRF	00.043	00.044
First-year expense, FAC (\$)	08.11	13.54
S (\$), salvage value	26.55	55.34
SFF, or sinking fund factor	00.021	00.021
ASV (\$, or annual salvage value	00.462	00.867
maintenance factor annually, MC	0.13	0.14
Cost of annual maintenance, AMC (\$)	01.19	01.89
Total yearly expense (\$)	08.76	12.53

Table 6
Annual production for CPL in DSBD.

Distiller units	(L/m ² .year), M.	(\$/L/m ²), CPL.
References (29/6),	197.53	00.051
Coating glasses, (12 W),	283.1	0.049
References, (1/7),	169.11	00.049
Coating glasses (36 W),	374.82	00.038

Table 7
Results for coated ZPBN in DSBD in terms of economics and the environment.

Parameter	Summer	Coated ZPBN	winter	DSBD
E _{out} , annual (kWh)	32.38	48.22	28.15	63.36
Ex _{out} , (kWh) yearly	10.97	14.51	16.22	17.21
(\$),TAC.	08.65	14.53	08.85	14.53
(kWh/\$), R _{en} .	03.65	03.44	03.23	04.53
(kWh/\$), R _{ex} .	01.29	00.87	01.81	01.24
Mitigated CO _{2ex} , lifetime (tonnes CO ₂)	01.59	02.31	01.39	02.85
Reduces CO _{2ex} . throughout a lifetime (in tonnes CO ₂).	00.39	00.22	00.56	00.33
Z _{CO2} , (\$.) energy.	47.56	61.34	38.48	81.35
Z _{CO2} , (\$.) exergy	13.35	03.81	18.79	07.45

Table 8
Compares the results of the current investigation with those of a prior study using coating materials (n = 30 years).

Parameters	Summer/ winter	Coated ZPBN	Furqan Jamil et al., (Jamil et al., 2023), Absorber plate coated materials
Energy contained (kWh.)	138.43	423.75	851.12
Yield per year, M. (L/m ² .year.)	169.10	379.34	381.12
E _{out} , annual (kWh)	28.15	63.36	246.25
Ex _{out} , annual (kWh)	15.19	18.17	28.79
EPBT _{en}	4.89	6.55	3.42
EPBT _{ex}	9.06	22.83	28.79
EPF _{en}	0.20	0.15	0.29
EPF _{ex}	0.11	0.04	0.03
Mitigated CO _{2ex} , natural life (tones CO ₂)	01.39	02.89	14.12
mitigates CO _{2ex} , natural life (tones CO ₂)	00.59	00.31	00.069
CPL (\$/L/m ²)	0.051	0.036	0.243
(kWh/\$.), R _{en} .	03.35	04.55	02.56
(kWh/\$.), R _{ex} .	01.69	01.41	00.29
Energy (\$), Z _{CO2}	38.64	81.34	188.81
Exergy, (\$), Z _{CO2}	18.79	07.30	01.21

4.5.2. Energy efficiency analysis

Energy efficiency improvements of the DSBD units with ZPBN-coated absorber plates were quantified, revealing an enhancement of 16.4%

during the summer season and 14.1% during the winter season, respectively. These values were determined by assessing the energy output of the distillation process with the ZPBN-coated absorber plate in comparison to the uncoated counterpart.

4.5.3. Exergy efficiency assessment

The exergy efficiency of the DSBD units was also evaluated, both with and without ZPBN coatings, during both summer and winter periods. The DSBD units coated with ZPBN exhibited an exergy efficiency of 2.1% during summer and 1.9% during winter. In contrast, DSBD units without ZPBN coatings demonstrated higher exergy efficiencies, measuring 7.4% during summer and 6.4% during winter, Soumyajit Koley (2022).

4.5.4. Effect of ZPBN concentration

Furthermore, the effect of varying ZPBN concentrations (05%, 10%, 15%, and 20%) on the exergy efficiency of DSBD units was analyzed. Fig. 5(d) illustrates that the exergy efficiency of DSBD units with 05% ZPBN concentration was 3.8% in winter, while it measured 3.4% for 10%, 2.8% for 15%, and 4.8% for 20%. Interestingly, despite the coated ZPBN absorber plate in DSBD, a reduction in energy efficiency was observed when compared to other concentration ratios, indicating potential fluctuations in the system's performance over time, Arunkumar et al. (Arunkumar et al., 2020). These experiments provide valuable insights into the impact of ZPBN coatings on the energy and exergy efficiency of DSBD units, shedding light on the dynamic behaviour of the system under varying conditions.

5. Conclusion and remarks

One of the primary global challenges today revolves around the scarcity of water resources. Utilising Double Slope Single Basin Solar Distillers (DSBD) for extracting potable water from saline sources stands as an effective solution to address this issue. Numerous strategies are employed to enhance the freshwater production efficiency of solar stills. This study delves into the assessment and impact evaluation of an absorber plate coated with ZPBN (ZnO/PVC/Bioactive Nanocomposite) in conjunction with DSBD. The effectiveness of DSBD is rigorously examined during the winter and summer seasons spanning from 2022 to 2023, under consistent climatic conditions akin to those of KLEF, Vijayawada, India. Comparative analyses are conducted with traditional solar stills. Over the course of the experimental period, various parameters are meticulously measured and different scenarios are explored, encompassing both ZPBN-coated and uncoated absorber plates, with temperatures maintained at 68 °C (winter) and 78 °C (summer)."

A consequence collected demonstrated what follows:

1. Freshwater Productivity Evaluation:

The cumulative freshwater productivity of the Double Slope Single Basin Solar Distiller (DSBD) is assessed, yielding 2.27 l/m² per day during the winter and 2.62 l/m² per day in the summer. In the presence of ZPBN coating, an enhancement of 14% and 17.5% in freshwater output is observed for the winter and summer, respectively.

2. Impact of ZPBN and Temperature:

The influence of ZPBN coating, applied at average absorber plate temperatures of 68 °C and 78 °C for winter and summer, respectively, is examined. This augmentation results in a remarkable cumulative DSBD production increase of 172.5% for winter and 158.8% for summer.

3. Cost Analysis:

Cost analysis is performed by calculating the cost per litre of fresh-water produced using DSBD. Notably, the exergoeconomic value of DSBD surpasses that of the Conventional Double Slope Single Basin Solar Distiller (CDSBD), particularly with lower ZPBN applied at 65 °C.

4. CO₂ Mitigation:

In scenarios involving conventional solar desalination, the maximum CO₂ mitigation is estimated at approximately 160 tonnes and 28 tonnes, respectively.

5. Exergo-Enviroeconomics Parameter:

DSBD cases are subjected to an exergo-enviroeconomics analysis, yielding values of \$20.70, \$37.30, \$70.80, \$104.40, and \$148.30.

Recommendations for future work

Investigate the modification of solar stills through the utilization of metal oxide materials mixtures, aimed at developing a PVC/Bioactive Nanocomposite with nano matrix composites materials for optimized solar absorption. Conduct an exhaustive investigation into the DSBD process to uncover valuable insights for prospective research initiatives. Explore the use of solar distillation technology for the treatment of wastewater and other contaminated water sources. Recommendations for future work in the realm of cleaner production technologies involve the integration of solar distillation systems with various renewable energy sources, including wind and biomass, to create a more comprehensive and sustainable energy solution. Investigate the use of nanomaterials and other advanced materials to improve the performance of solar stills.

CRedit authorship contribution statement

Ravinder kumar: Conceptualization, Methodology, Software, Writing – review & editing. **Ashish Maurya:** Methodology. **S. Shanmugan:** Conceptualization, Methodology, Software, Supervision, Writing – original draft, Funding acquisition, Writing – review & editing. **Abd-Elnaby Kabeel:** Funding acquisition, Writing – review & editing. **Zhumatova Assel Akanovna:** Writing – review & editing. **Yerlan Sarsenbayev:** Supervision, Writing – original draft. **Hitesh Panchal:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Nomenclature

A	Basin area (m ²)
η	Energy efficiency in real-time (%)
m_w	Mass output (kg)
$I(t)$	Solar radiation (W/m ²)
h_{fg}	Heat transfer from basin to glass covers (W/m ² K)
D	X-rays wavelengths (1.58 Å)
-	Bragg's deflection position
-	semi limits
T_w	water temperature (°C)
T_a	ambient temperature (°C)
T_s	the sun's surface temperature (K)
A_s	Basin surface area (m ²)

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