Preparation of New Nano-Enhanced Phase Change NePCMs by Modifying Paraffin Wax with Both Nano Fe_2O_3 and Silver-Coated Nano Fe_2O_3 and Studying Their Effect on the Efficiency of the Photovoltaic System

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Abstract

Phase change materials (PCMs) significantly improve the efficiency of solar energy systems through thermal regulation. However, their low thermal conductivity limits their use. To overcome this limitation, various studies have focused on enhancing the thermal properties of PCMs by adding nanoparticles, creating nano-enhanced phase change materials (NePCMs).

This study aimed to synthesize nanoparticles of iron oxide (Fe_2O_3), coat them with silver (Fe_2O_3-Ag), and investigate the effect of incorporating these nanoparticles into paraffin wax to form two types of NePCMs (PCM-NFe_2O_3 and PCM-NFe_2O_3-Ag). The impact of these NePCMs on the efficiency of a conventional photovoltaic (PV) module was also examined. Results showed that adding Fe_2O_3 and Fe_2O_3-Ag significantly increased the thermal conductivity of paraffin wax. The thermal conductivity of pure paraffin wax was 0.4857 W/mK, increasing to 2.07 W/mK and 2.44 W/mK when 2% Fe_2O_3 and Fe_2O_3-Ag were added, respectively. However, adding a higher percentage led to a decrease in thermal conductivity due to nanoparticle agglomeration.

By monitoring the temperature of the PV module (test model), results demonstrated the effectiveness of the proposed cooling system. The temperature of a conventional PV module reached 62.32°C, while a PV module using PCM with 2% NFe_2O_3 exhibited a reduced temperature of 40°C. The best performance was observed in the PV module using PCM + 2% NFe_2O_3-Ag, where the temperature decreased to 39°C. This improvement was reflected in the module's performance. The power output of the PV module with a cooling system, particularly the PCM + 2% NFe_2O_3-Ag system, reached 34.73 watts, compared to 29.62 watts for the conventional PV module. This represents a 17.25% increase in energy production using the same PV module area, contributing to more efficient land or roof space utilization for solar panel installation.

Keyword: NePCMs, Photovoltaic System, PCMs, paraffin wax.

Introduction

The creation of thermally efficient and cost-effective energy storage systems is required due to the widening disparity between the world's energy supply and demand. Sensible heat storage, latent heat storage, and thermal-chemical energy storage are the three primary techniques for storing thermal energy. Because of their high latent heat storage capacity, which enables them to absorb or release sizable amounts of heat during phase transitions like melting or solidification, phase change materials (PCMs) are becoming more and more popular in thermal energy storage (TES) systems [1]. Latent heat energy storage methods using PCMs have drawn interest for solar energy applications because of their environmentally friendly and sustainable qualities [2]. Thermal energy storage systems are crucial for global sustainability initiatives since they reduce energy consumption [2]. Higher heat storage capacity, less storage area needed, lower working temperatures, and isothermal operation are some benefits of PCMs. Low thermal conductivity, phase segregation, sub-cooling, volume fluctuations, and high prices are some of the difficulties that their practical uses must overcome [3]. Many cooling strategies have been researched to lower operating temperatures and increase PV panel efficiency. These consist of heat pipes for cooling concentrated PV cells, water cooling using circulators, and air cooling (both natural and forced convection) [3, 4]. Active cooling methods like water spraying on PV modules [5,6] or using air ducts with manifolds to improve airflow distribution have been studied in some detail. In solar modules, these techniques have shown notable temperature reductions and efficiency gains [7–10]. A study tried to increase the efficiency of photovoltaic panels by spraying them with water. The motor is started by the temperature sensor when the PV panel temperature reaches the maximum permitted temperature of 45°C, which cools the PV cell to its typical operating temperature of 35°C [11]. An active cooling system for solar modules was created by another investigation. The experiment was conducted both with and without active cooling. The back of the PV module has a parallel array of ducts with input and exit manifolds intended for uniform air flow distribution. The module's temperature was high in the absence of active cooling, and the solar cell's efficiency was between 8 and 9%. The PV module's temperature decreased considerably when it was run under active cooling conditions, and the solar cell's efficiency reached 12–14% [12]. Both numerical and experimental studies were conducted to assess the performance of PV modules using back surface water cooling in hot climates. The results showed good agreement between the two methods. In the case of the active cooling technique, the operating temperature of the module decreased significantly to around 20%, and an increase of 9% in electrical efficiency was noted [13]. A heat exchanger with water as the working fluid was used in an experiment to control the temperature of photovoltaic modules in order to increase energy yield. The heat exchanger was mounted on the back side of the PV module and had a single pass heat exchanger system; this resulted in a reduction of 18–20^{o}C in the operating temperature of the module and an increase in power output of almost 10% [14]. When a material transitions from a solid to a liquid or from a liquid to a gas, thermal energy is stored in phase change materials (PCMs), which have the capacity to store energy at a high density as latent heat [9].

Heat is either absorbed or released as a result of the material phase transition. Because it can store five to fourteen times the amount of heat per unit volume, latent heat is superior to sensible heat [10]. The temperature in PCMs is kept almost constant throughout the phase transition. Thus, one of the most crucial strategies used in the efficient thermal management of these devices for their safe and dependable functioning is the addition of PCMs to devices that produce a lot of heat, such electrical gadgets [15]. High storage density, consistent temperature, and reusable technology are the benefits of employing latent thermal storage. It is thus advised to utilize it, However, phase change materials should be packed to prevent contamination and leakage of the liquid phase, particularly when the PCM contains water to stop water absorption or evaporation [16]. The three categories of phase change materials (PCMs) are as follows: eutectic (organic–organic, organic–inorganic, and inorganic–inorganic compounds), organic (paraffin, stearic acid), and inorganic (hydrate, molten salt, metal) [16]. Many kinds of phase change materials, including inorganic and organic ones, have been thoroughly studied to determine their potential for use as energy storage materials. Since paraffin wax has a higher energy density, lower vapor pressure, better chemical and thermal stability, less supercoiling, non-toxicity, wide availability, and low cost, most researchers have experimented with it as an energy storage medium. Their limited heat conductivity is a drawback, even if paraffin has the previously noted excellent quality. Paraffin was mixed with several nanomaterial additions, such as nano Al_2O_3, nano ZnO_2, and nano SiC, and the resulting changes in the nanomaterials' thermophysical characteristics were examined [17]. According to the findings of these investigations, the product's thermal conductivity increased while the nano-PCM mixes' heat capacity increased very little. Numerous solar applications have made use of nano-PCM, and research has indicated that the pace at which the product's stability and thermal conductivity increase varies significantly [17, 18]. An investigation into the performance enhancement of paraffin wax using nano-alumina (Al_2O_3) particles at varying mass concentrations of 1, 3, and 5% revealed that the addition of alumina nanoparticles up to 14% improved the thermal performance of paraffin wax to some degree and demonstrated the enormous potential of nanoparticle-enhanced PCM for a variety of energy storage applications [18]. In electronic cooling applications, the addition of 0.5 and 1% of Al_2O_3 nanoparticles to paraffin waxes, known as nano-PCMs, has been studied experimentally and scientifically. The results showed that the nano-PCMs could slow down the melting process with a lower mean temperature than pure PCMs [19]. According to research on the impact of adding varying weight percentages of different nanoparticles, including CuO, TiO_2, Al_2O_3, and graphene, to paraffin on improving PCM's thermal properties, the main applications for nano-enhanced PCMs may be those where temperature control is essential [20]. copper nanoparticle dispersion in the RT24 PCM base fluid. They found that the melting and solidification rates of this nano-enhanced PCM are greater than those of the pure PCM. In comparison to the pure PCM, it was discovered that the nano-enhanced PCM charged 8.3% more heat and released 25.1% more heat [21]. The dispersion of 2.0% mass fraction of multi-walled carbon nanotubes in paraffin wax enhanced the thermal conductivity ratios to 35–40%, according to the results of a recent study. Paraffin's thermal characteristics were enhanced by the addition of zinc oxide nanoparticles, and it was proposed that this material might work well for solar thermal energy storage applications [1,3].

By reviewing previous studies, it was observed that most research lacked the incorporation of hybrid nanoparticles with paraffin wax for cooling PV systems. Therefore, this study aims to compare nano-iron oxide and silver-coated iron oxide as additives in paraffin wax to enhance PCM performance and improve the efficiency of conventional PV modules.

Materials and Methods

Preparation of Fenugreek Seed Extract

Fenugreek seeds were washed multiple times with deionized water, dried at room temperature, and ground into powder. A total of 30 g of the powdered seeds was mixed with 100 mL of deionized water and stirred at 60°C for 2 hours. The mixture was then filtered, and the extract was stored in a closed container for further use.

Synthesis of Nano Fe_2O_3

A solution of 10 g of hydrated ferric chloride ($FeCl_3.6H_2O$, 97% purity, Sigma-Aldrich) was prepared in 50 mL of deionized water and stirred for 10 minutes. Then, 20 mL of the previously prepared fenugreek seed extract was added dropwise while stirring continuously at 60°C. After 2 hours of stirring, the pH was adjusted to 9 using ammonia solution, and stirring continued for another 2 hours. The solution was cooled, filtered, and the resulting precipitate was dried in an oven at 100°C. The dried sample was then calcined at 400°C for 180 minutes. The oxide was ground and stored in a moisture-free environment for further experiments.

Preparation of Nano Fe_2O_3-Ag

A total of 5 g of prepared nano Fe2O3 was dispersed in 50 mL of deionized water using ultrasonication for 15 minutes. Then, 0.05 g of silver nitrate (AgNO3, 99% purity, Sigma-Aldrich) was added to the solution, followed by 20 mL of fenugreek seed extract. The solution was stirred for 2 hours, filtered, and the resulting Fe_2O_3-Ag precipitate was dried at 60°C and stored in an opaque glass bottle away from moisture and light.

Characterization of Fe_2O_3, Fe_2O_3-Ag

The characteristics of nano Fe_2O_3 and Ag-Fe_2O_3 were determined using several techniques including: X-ray powder diffractometer (XRD) by PANalyticalX'Pert PRO MPD system, which implicated the 2θ values in a scale of 20˚ to 80˚ along with the Cu K_α radiation source (λ=1.54060) that functioned at 40kV and 25 mA, the average crystallite size (**D_{av}**) for prepared Fe_2O_3 calculated for (104) direction by Scherrer formula (2):

$$D_{av} = 0.9\ \lambda/\beta\ \cos\theta \ \ldots\ldots(2)$$

Where (β) is full width of half maximum (FWHM), (λ) wavelength for Cu target of XRD instrument. The morphology of samples was examined by Atomic Force Microscopy (AFM) micrographs which were recorded by using scanning probemicroscope type (Nano surf), the size of the prepared particles was determined using Zetasize Nano-ZS by Malvern Instruments.

Effect of prepared oxides on the thermal conductivity of paraffin wax

Paraffin produced by Kmart Chemical Technology Company was studied by preparing samples of modified paraffin wax with different amounts of prepared oxides (**Fe_2O_3, Fe_2O_3-Ag)** by (1, 1.5, 2, 2.5, 3)%, where the paraffin wax was melted in a water bath at 75°C, then the nanoparticles (Fe_2O_3, -Ag Fe_2O_3) were added with mechanical stirring until homogeneity, the mixture was poured into a mold with dimensions (14*14*1) cm. The thermal conductivity test was performed using single-plate method consisting of a thermal bath consisting of heating resistors with thermal sensors and an insulated chamber for the test sample. The modified and unmodified

paraffin samples were placed in the chamber of the device, then the temperature of both the upper and lower faces was determined by thermal sensors in contact with the two faces. The thermal conductivity was measured based on Fourier's Law according to the (1):
$Q=(K*A*\Delta T)/d$ …(1)
Where:
Q: Heat transfer rate (W),
k: Thermal conductivity coefficient (W/m·K)
A: surface (m^2)
ΔT: Temperature change (°C) between the two faces of the sample
d: Sample thickness (m)
Where the heat transfer rate Q was calculated using (2)
$Q=I*V$ …(2)
I current intensity (A), V voltage (V)

Design of the test model

Mono-crystalline silicon solar panels of dimensions (67x44.5x1.7) cm, with a power of 50W, open circuit voltage Voc (22V), open circuit current Isc (3A), manufactured by General Gold Company were used. The lower face of the solar panels was provided with an aluminum container of dimensions (64x42x0.5) cm for paraffin wax. The power output of the conventional PV module, the PV with paraffin wax cooling system PCM, PV with paraffin wax and NFe_2O_3 cooling system PCM-NFe_2O_3, and PV with paraffin wax and NFe_2O_3-Ag cooling system PCM-Fe_2O_3-Ag were compared.

The solar panels were installed at an angle of 33° to the south to obtain the maximum solar radiation. The temperatures were recorded using several Weewooday thermocouples installed at different positions to calculate the average temperature of the PV module at each reading. The voltage and current were measured with a DT830B Digital Multimeter with a range of (200µA-10A) (200mV-2000V). The electrical power output was calculated using (3), the experiment continued for 8 hours per day over three days.
$\mathbf{P_{max}=I_{max}*V_{max}}$ **…(3)**
Where:
P_{max}: maximum power generated by the panel (Watt)
I_{max}: maximum current intensity (A)
V_{max}: maximum voltage (V)
The average power change for each case was determined by (4):
$\mathbf{\Delta P=(P_{max2}-P_{max1})/P_{max1} *100}$**….(4)**
Where: P_{max2}: maximum power of the modified solar panel, P_{max1}: maximum power of the reference solar panel.

Results and Discussion

Fig. 1 demonstrated the X-ray diffraction (XRD) patterns of prepared nano Fe_2O_3, the diffraction results show the presence of several peaks in the 2θ positions of 24.21, 34.12, 35.58, 49.51, 53.71, 58.86, 63.54, and 61.28˚ that were associated with the (021), (104), (110), (024), (116), (018), (214) and (300) planes indicating that the nature of the prepared nano Fe_2O_3 structure was polycrystalline with hexagonal structure, when comparing the peaks with the standard card (JCPDS) (33-0664), it was found that the results were close to some extent. It was found that the crystallite size of prepared nano Fe_2O_3 28.53 nm. The 2D and 3D (AFM) images of prepared nano Fe_2O_3 confirm that the particle size exists in nano range, where it can be observed that the roughness calculated using (Imager4.62) software attached with the (AFM) device was 13.73 nm, the average particle size of the Fe_2O_3 calculated from (XRD) results nearly matches with (AFM) results as shown in Fig. 2.

The average sizes of the prepared NFe_2O_3 was determined using Dynamic Light Scattering (DLS) technique. According to Fig. 3 the average sizes was 33 nm which was confirmed with AFM.

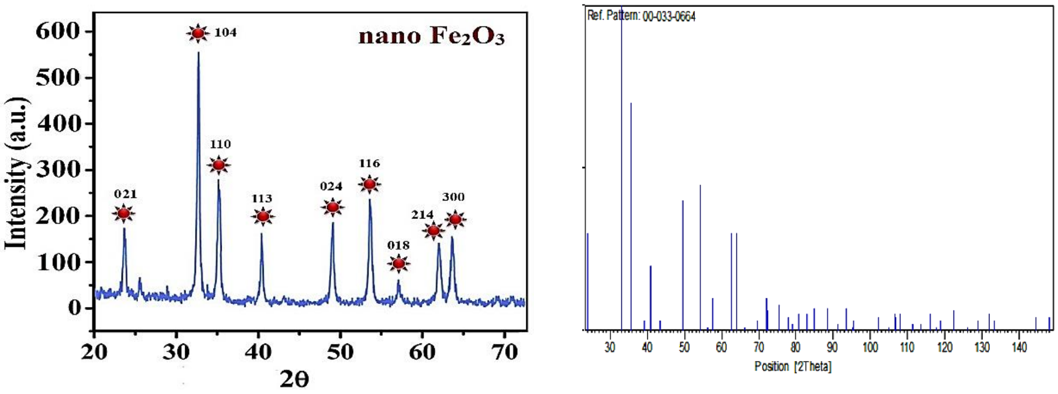

Figure 1. XRD of prepared NFe_2O_3, and JCPDS (33-0664)

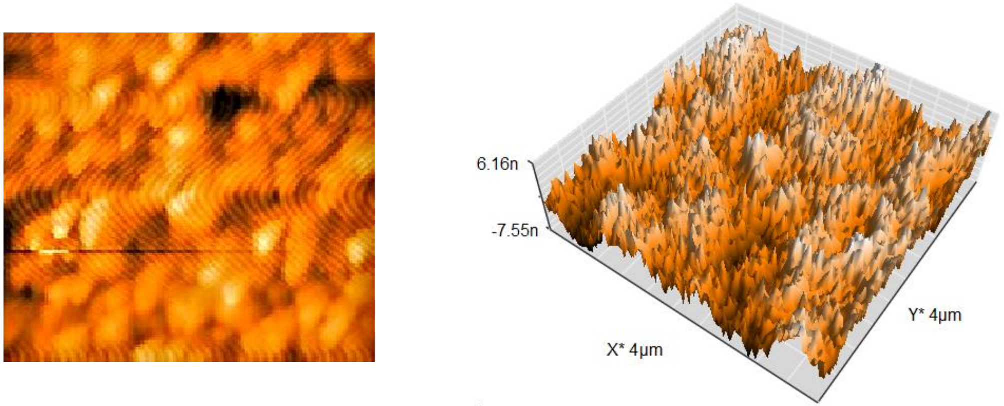

Figure 2.The 2D and 3D AFM images of prepared NFe_2O_3

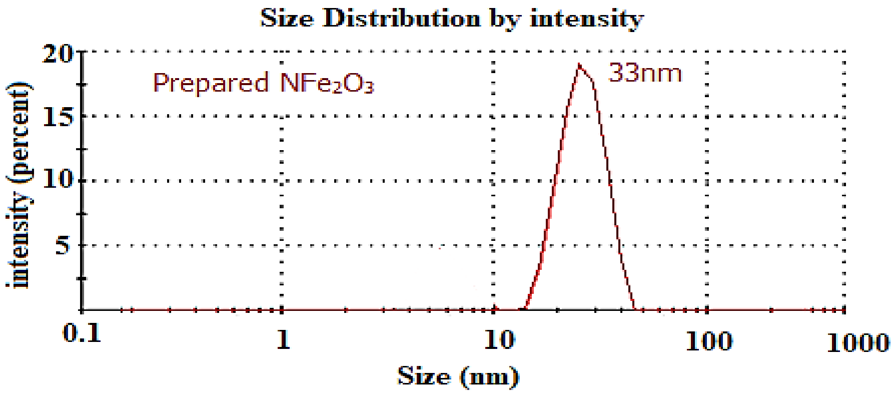

Figure 3. DLS of prepared NFe_2O_3

Fig. 4 exhibits the powder x-ray diffraction spectrum of nano Fe_2O_3-Ag, which displays serval peaks at the 2θ position of 38.1, 43.2, and 65.4° as the signs of silver atoms existence in the crystalline construction of nanoparticles, the crystalline particle size of Fe_2O_3-Ag was determined through the Debye-Scherer's, it was 88.41nm.

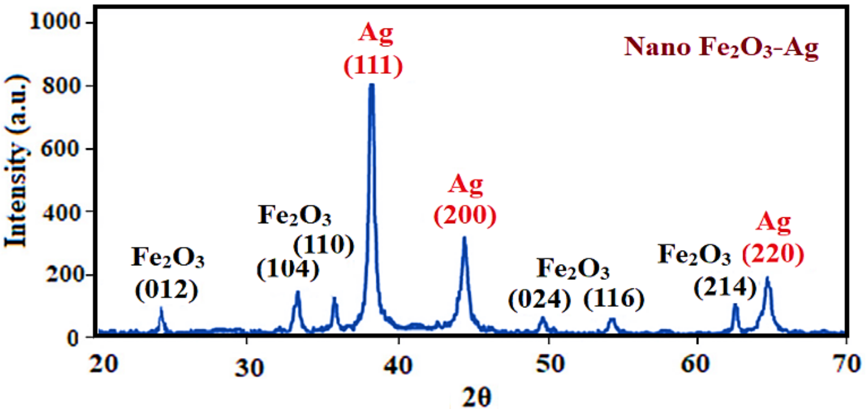

Figure 4. XRD of prepared nano Fe_2O_3-Ag

Results showed that adding both of (Fe_2O_3, Fe_2O_3-Ag) led to a significant increase in the thermal conductivity of paraffin wax, as the thermal conductivity of paraffin wax reached 0.4857 W/mK, increased to 0.98 W/mK when adding 0.5% nano, Fe_2O_3 continued until it reached 2.07 W/mK when adding 2%, to decrease to 1.18 W/mK when adding 2.5% due to the aggregation of the added nanoparticles and their lack of homogeneous distribution throughout the entire volume of paraffin wax, as they appear in the form of brown spots distributed in an inhomogeneous manner on the surface of the wax. The results also confirmed that adding Fe_2O_3-Ag affects the thermal conductivity to a greater degree, as it reached 2.44 W/mK when adding 2%, while adding a higher percentage does not give better results due to the agglomeration of the nanoparticles, meaning that adding 2% was considered the best Table 1.

Table 1. Thermal conductivity of normal paraffin and modified paraffin

Sample			**Thermal conductivity (W/mK)**
Paraffin%	**NFe_2O_3%**	**NFe_2O_3-Ag%**	
100	0	0	0.4857
99.5	0.5	0	0.98
99	1	0	1.27
98.5	1.5	0	1.67
98	2	0	2.07
97.5	2.5	0	1.18
99.5	0	0.5	1.29
99	0	1	1.48
98.5	0	1.5	1.98
98	0	2	2.44
97.5	0	2.5	1.65

Effect of designed cooling system on the performance of the photovoltaic PV

By monitoring the temperature of PV module (test model) results showed the good effect of the proposed cooling system, where the temperature of the conventional PV reached to 62˚C at 15:00, while the temperature of the PV with PCM (paraffin 100%) was 52˚C, but when using PCM (paraffin + 2%NFe_2O_3) the temperature was 40˚C, while PV with PCM (paraffin +2%NFe_2O_3-Ag) proved to be the best as the temperature of the photovoltaic module reached only 39˚C, meaning that this cooling system contributed to reducing the temperature by 23.32˚C Table (2)

Table 2. Temperature of studied PV

Time	**PV Temperature (C˚)**			
	Normal PV	**PV + PCM (paraffin 100%)**	**PV + PCM (paraffin + 2%NFe_2O_3)**	**PV + PCM (paraffin +2%NFe_2O_3-Ag)**
09:00	31	25	23.99	23.0
10:00	35	28	27	26
11:00	38	33	31	30
12:00	46	37	35	34
13:00	53	40	41	39
14:00	61	47	46	44
15:00	62	52	40	39
16:00	52	40	38	37

The results showed that the decrease in the temperature of the PV was reflected in its performance. The power of the PV with a cooling system, especially the PCM (paraffin +2%NFe_2O_3-Ag) system was reached to 34.73 watts, while the power of the conventional PV was 29.62 watts, so there was an increase in energy production by 17.25% using the same area of the photovoltaic module, which contributes to saving the land or roof space used to install the panels. Table (3)

Table 3. Average power of studied PV

Time	**Average power of PV ΔP (watt)**

	Normal PV	PV + PCM (paraffin 100%)	PV + PCM (paraffin + 2%NFe_2O_3)	PV + PCM (paraffin +2%NFe_2O_3-Ag)
09:00	20.10	22.55	23.53	24.50
10:00	23.44	24.83	26.64	27.70
11:00	27.85	30.25	32.14	33.40
12:00	28.93	31.34	32.55	33.76
13:00	29.62	32.56	33.45	34.73
14:00	25.55	29.32	29.91	31.08
15:00	19.15	21.18	21.88	22.94
16:00	12.93	14.13	14.84	15.44

Results showed that the addition of Fe_2O_3 and Fe_2O_3-Ag significantly enhanced the thermal conductivity of paraffin wax. The conductivity increased from 0.4857 W/mK for pure paraffin to 2.07 W/mK and 2.44 W/mK with 2% Fe_2O_3 and Fe_2O_3-Ag, respectively. However, adding higher percentages led to decreased thermal conductivity due to nanoparticle agglomeration.

The proposed cooling system also improved PV module performance. The temperature of a conventional PV module reached 62°C at peak operation, while the temperature of a PV module incorporating PCM (paraffin + 2% N Fe_2O_3) decreased to 40°C. The best results were obtained with PCM (paraffin + 2% N Fe_2O_3-Ag), which reduced the module temperature to 39°C. This reduction in temperature led to a 17.25% increase in energy production, with the PV module output increasing from 29.62 W to 34.73 W.

Conclusions

This study successfully synthesized and tested two types of nano-enhanced phase change materials (NePCMs) by modifying paraffin wax with nano Fe_2O_3 and Fe_2O_3-Ag. The addition of these nanoparticles significantly improved the thermal conductivity of paraffin wax and enhanced the efficiency of photovoltaic modules. The best results were obtained with PCM + 2% NFe_2O_3-Ag, which reduced PV module temperature and increased power output, demonstrating the potential of hybrid NePCMs for solar energy applications.

Ethics approval: Not applicable
Consent to participate: Not applicable
Consent for publication: We agree to publish in accordance with the terms and conditions of the journal
Availability of data and materials: Data collection is available in the text
Competing interests: No conflict of interest with any party or person
Funding: No Funding
Authors' contributions:
Abdulrazzaq Hammal: Chemical Experiments and Writing
Bahia Sheikh Alkassabeen: Electrical Tests
Khaldoun Hafez: Electrical Tests

Acknowledgements
We thank the University of Aleppo, Syria

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