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Enhanced Efficiency of Photovoltaic Thermal Systems using Graphene Nanoplatelets Nanofluids

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ABSTRACT

Photovoltaic thermal (PV/T) systems have become a promising technology for using solar radiation to generate thermal and electrical energy. However, the overheating tendency of PV cells can reduce the electrical output of PV/T systems, thereby limiting their efficiency. One way to increase the efficiency of PV/T systems is the utilization of nanofluids as the working fluid. This investigation uses water-based nanofluids based on graphene nanoplatelets to study the efficiency of PV/T systems. Graphene nanoplatelets (GNP), the nanofluids, were prepared at a mass fraction of 0.6 wt.%, which, due to its thermophysical characteristics, was determined to be the ideal weight percentage. The surfactant utilized in this study was polyvinylpyrrolidone (PVP) to improve the stability of the nanofluid and an amount of 40% from the GNP weight percentage was used as the weight percentage of the surfactant. The two-step method is implemented to formulate the nanofluid. The results obtained shows that the GNP/water nanofluids provide better thermal and electrical efficiency compared to distilled water with the highest thermal and electrical efficiency obtained was 80% and 8.9%, compared to water, 66.5% and 8.8%, respectively, and the overall enhancement of 17% at different flow rates and solar irradiance levels, emphasizing the significant role of nanofluid technology in advancing the sustainability and effectiveness of solar energy applications. This proved that the nanofluid could boost energy conversion and system efficiency because of its increased thermal and electrical efficiencies.

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1. Introduction

The global energy landscape is shifting toward sustainable and renewable energy sources to address the dual challenges of climate change and depleting fossil fuels. The need for alternative energy sources has been brought to light by recent global energy crises, and photovoltaic thermal (PV/T) systems have gained popularity because of their ability to reduce the consumption of electricity, natural gas, and fossil fuels. PV/T systems have emerged as a promising technology for harnessing both electrical and thermal energy from solar radiation [1]. Photovoltaic (PV) cells and a thermal collector are combined in these hybrid systems to enable the simultaneous production of heat and electricity [2]. Despite these advantages, conventional PV/T systems face limitations in their energy conversion efficiency due to suboptimal thermal management, where the excess heat generated during photovoltaic operation reduces electrical efficiency and is not effectively utilized [3,4]. The PV cells' tendency to overheat can limit the PV/T systems' efficiency by lowering their electrical output [5,6]. This has necessitated the exploration of advanced cooling strategies and working fluids to optimize the thermal and electrical performance of PV/T systems.

The utilization of nanofluids, which are engineered fluids with nanometer-sized particles distributed in a base fluid, is one of the methods to increase the heat transfer rate of several devices, thus can be used for improving the efficiency of PV/T systems [7,8]. These fluids exhibit superior thermophysical properties, such as enhanced thermal conductivity, higher heat transfer coefficients, and improved stability, compared to conventional fluids [9]. By increasing heat transfer and energy efficiency, the use of nanofluids, particularly graphene nanoplatelets, can improve the thermal performance of PV/T systems. The remarkable thermal and electrical properties of graphene nanoplatelets (GNP) have attracted a lot of interest due to their extraordinary thermal conductivity, large surface area, and chemical stability [10]. The incorporation of GNP into the working fluid of a PV/T system can potentially improve the heat transfer characteristics, leading to enhanced thermal and electrical performance [11-13]. By lowering the operating temperature of photovoltaic modules, these nanofluids can mitigate thermal degradation of electrical efficiency while also increasing thermal energy output, leading to enhanced overall system performance.

The use of nanofluids in PV/T systems has been studied in the past, with a focus on a number of variables, such as the effect of the base fluid, concentration, size, and shape of the particles on heat performance [14,15]. In order to maximize performance and sustainability, a number of factors must be evaluated during the complex process of choosing materials and thermophysical considerations for sustainable nanofluids [16]. Research indicates, for example, that the thermal conductivity and energy conversion efficiency of PV/T systems can be greatly increased by the addition of nanoparticles such as metal oxides or carbon nanotubes (CNT) [17-19].

The integration of the PV/T systems holds immense potential for enhancing energy conversion efficiency and sustainability in various applications. In recent years, the utilization of nanofluids, particularly those incorporating GNP nanofluids, has emerged as a promising strategy to improve the performance of PV/T systems. By leveraging the unique thermal and electrical properties of GNP, researchers have aimed to optimize the overall efficiency of these systems.

The use of GNP nanofluids in PV/T systems offers several advantages, including enhanced thermal conductivity, improved dispersion stability, and increased surface area for heat transfer. GNP is a desirable option for improving the thermal performance of PV/T systems since it has been demonstrated that they have high specific surface area and high heat conductivity [20]. Several studies have demonstrated the potential of GNP-based nanofluids in energy systems. For instance, Alshikhi and Kayfeci [21] developed an experimental setup to study the effects of GNP nanofluids, distilled water, and hybrid nanofluids (Al_2O_3 and GNP) as coolants in PV/T collectors. According to the

study, the GNP nanofluid outperformed the other fluids tested in terms of thermal efficiency, making it the most efficient fluid overall. Abd Elhafez *et al.*, [22] reported a substantial improvement in heat transfer characteristics using GNP nanofluids in a heat exchanger application, while Dhayanidhi and Selvam [23] highlighted the long-term stability and high thermal conductivity of GNP nanofluids for cooling applications. However, the application of GNP nanofluids in PV/T systems remains relatively underexplored, particularly in terms of their performance under varying solar irradiance levels and operational conditions. This study aims to address these gaps by investigating the formulation and integration of GNP nanofluids as working fluids in PV/T systems.

This study uses GNP water-based nanofluids as the working fluid to examine the performance of PV/T systems. The analysis's focus will be on how different factors, like solar irradiance and mass flow rate, affect the system's thermal performance. The findings of this research will bring important new light on how graphene nanoplatelets and nanofluids might improve the sustainability and efficiency of PV/T systems.

2. Methodology

2.1 Formulation of GNP Nanofluids

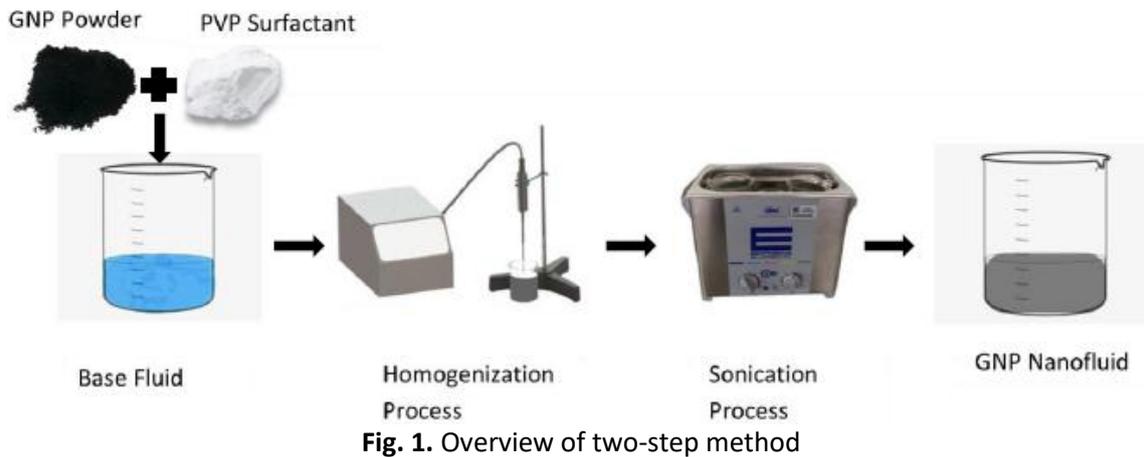
The two-step method, which disperses nanoparticles in a fluid, was employed in this study to formulate the GNP nanofluids as it is a widely used method in other research studies [24-27]. Figure 1 shows the overview setup of the two-step method. The two-step method involves the homogenization and sonication process to help achieve a stable nanofluid for further analysis. The nanofluid used in this study is graphene nanoplatelets (GNP) while the base fluid is distilled water. GNP is mixed with water with the addition of surfactant, polyvinylpyrrolidone (PVP), to maintain the stability of the nanofluid.

The nanofluids were homogenized using HG-15D homogenizer for 15 minutes at a speed of 1500 rpm at room temperature and they were sonicated for 30 minutes using Elmasonic E-30 H sonicator.

The mass/volume fraction or concentrations are calculated using the equation as stated in Eq. (1) as referred to Sandhya *et al.*, [28].

$$\phi = \left[\frac{\frac{w_p}{\rho_p}}{\frac{w_p}{\rho_p} + \frac{w_{bf}}{\rho_{bf}}} \right] \times 100 \quad (1)$$

In this equation, ' ϕ ' is the concentration, ' w_p ' is the weight of nanoparticles, ' ρ_p ' is the density of nanoparticles, ' w_{bf} ' and ' ρ_{bf} ' are the weight and density of the base fluid, respectively.



2.2 Performance Assessment of the PV/T Systems

The experiment is carried out both with and without the use of nanofluid in order to compare the systems’ performance. The NSD-15W polycrystalline PV/T module, as shown in Figure 2, is made up of a copper serpentine tube with an inner diameter of 10 mm and a thickness of 1 mm that is firmly welded to a copper plate. Copper tubes are used for the fabrication of the module due to its better thermal conductivity and ease in fabrication [29]. The specifications of the PV panel are as shown in Table 1.



Fig. 2. PV/T used in the study

Table 1
 Specifications of the PV panel

Solar module type	NSD-15W Polycrystalline Silicon
Peak power	15 W
Maximum power voltage	6 V
Maximum power current	2.5 A
Open circuit voltage	7.2 V
Short circuit current	2.75 A
Tolerance	±5%
Operating temperature	-20°C to 90°C

The indoor experiment is essential due to its flexibility of time and location. The experimental setup features 12 halogen lamps, with a power rating of 500 W each. Figure 3 shows the schematic diagram of the experimental setup while Figure 4 shows the real indoor experiment setup. The

experiment is conducted in a 25°C controlled environment. This experiment is carried out to collect heat from the PV/T at the irradiance range of 200 to 800 W/m² and the flow rate of the fluid varies from 20 to 80 L/hr. For greater accuracy, data from the experiment is collected every minute. Each measurement that is made has a record controlled and saved by the data logger. A voltage regulator allows the adjustment of the lamp intensity that ranges from 100 to 900 W/m². The Array 3721A 400-Watt Programmable DC Electronic Load was used to evaluate the PV/T system's performance. Using this device makes it possible to measure the I-V (current-voltage) curve precisely, which gives important insights into the electrical properties and functionality of the systems. The I-V curve can be plotted to analyze parameters like maximum power point, efficiency, and operating range by applying different load conditions and measuring the corresponding voltage and current values.

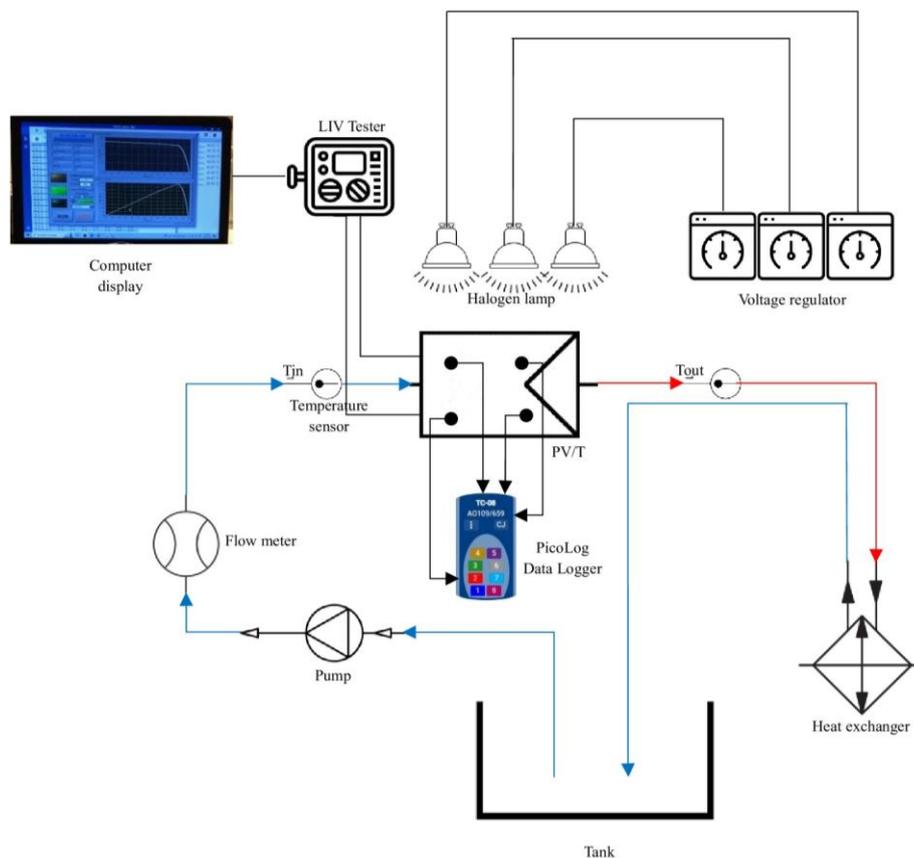


Fig. 3. Schematic diagram of indoor experiment setup

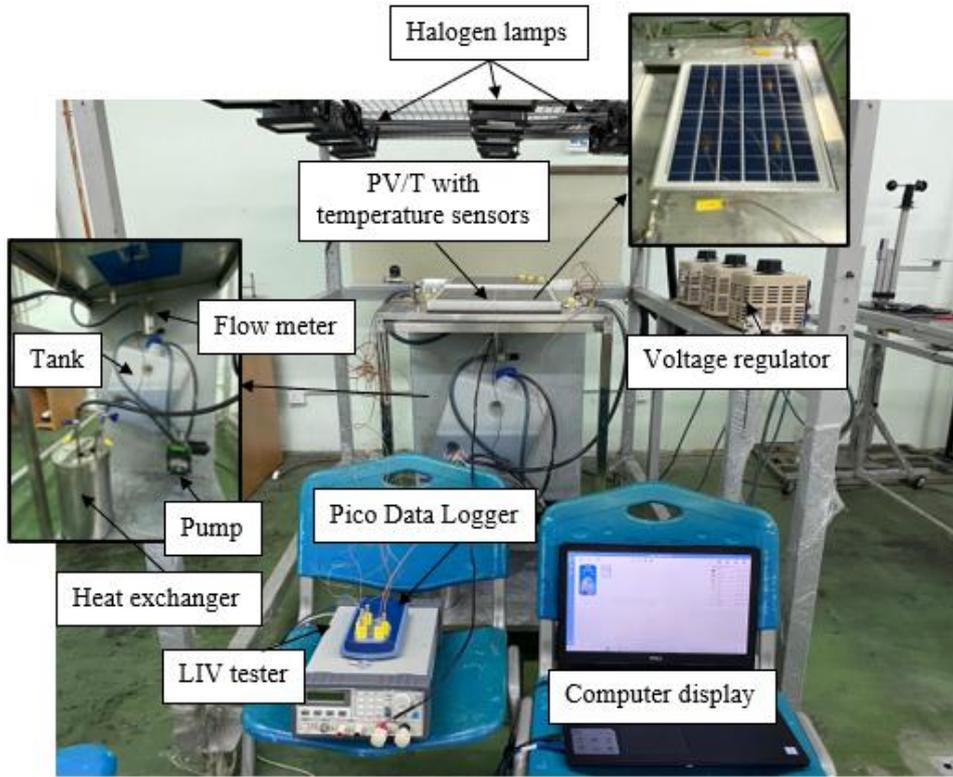


Fig. 4. Indoor experiment setup

The overall performance of the PV/T is evaluated by considering the electrical efficiency and thermal efficiency of PV/T. The electrical efficiency (η_e) is defined as in Eq. (2) and Eq. (3) as referred to Al-Waeli *et al.*, [30]:

$$P_{max} = V_{oc}I_{sc}FF = V_{max}I_{max} \quad (2)$$

$$\eta_e = \frac{P_{max}}{AI_a} \quad (3)$$

where P_{max} is the maximum electrical power, V_{oc} is the open-circuit voltage, I_{sc} is the short-circuit current, and FF is the fill factor. An IV tracer is used as the measuring equipment for electrical efficiency, providing the maximum voltage (V_{max}), maximum current (I_{max}), and maximum electrical power (P_{max}) values. To obtain the thermal efficiency (η_{th}) of the PVT system, the collected heat (Q_t) is calculated by Eq. (4):

$$Q_t = \dot{m}C_p(T_o - T_i) \quad (4)$$

where \dot{m} is the mass flow rate, C_p is the specific heat capacity, and T_o and T_i are the temperatures of the working fluid located at the outlet and inlet of the heat absorbing tube. The thermal efficiency of the PVT system is defined by Eq. (5):

$$\eta_{th} = \frac{Q_t}{AI_a} \quad (5)$$

where A is the collector area and I_a is the solar irradiance. The overall efficiency (η_o) is expressed as the sum of electrical and thermal efficiency as in Eq. (6):

$$\eta_o = \eta_e + \eta_{th} \quad (6)$$

2.3 Statistical Analysis

To evaluate the significance of various factors affecting the performance of the PV/T system, analysis of variance (ANOVA) and regression analysis was conducted using DesignExpert 13.0 software. This statistical method was used to analyse the influence of key variables, such as flow rate, solar irradiance, and type of fluid used on the thermal and electrical efficiency of the system.

The ANOVA was performed using a 95% confidence level ($p < 0.05$) to determine whether the observed differences in performance metrics were statistically significant [31]. The independent variables included flow rates (20–80 L/hr), solar irradiance levels (200–800 W/m²) and type of fluid (GNP nanofluid and distilled water), while the dependent variables were thermal efficiency and electrical efficiency.

3. Results and Discussions

3.1 Formulation of GNP Nanofluids

The result shows that the mixture of GNP/water nanofluid with 0.6 wt.% has the best thermophysical properties with the thermal conductivity of 0.6611 W/mK and viscosity of 1.22 mPa.s. The GNP nanofluids at a concentration of 0.6 wt.% also showed the highest degree of stability out of all the tested formulations. Based on this evaluation, the nanofluid was selected as the most promising mixture for further investigation to assess their thermophysical properties. The goal is to determine which nanofluid performs better in terms of heat transfer, viscosity, and other parameters relevant to PV/T systems. By conducting a thorough analysis of the thermophysical properties of the nanofluid, it helps to identify the nanofluid that offers superior thermal performance and the stability for the PV/T system. The results of other formulated nanofluid along with the thermophysical properties as reported in previous study [32,33].

3.2 Performance Evaluation of PV/T Systems using GNP Nanofluids

3.2.1 Thermal efficiency

For measurement of PV/T efficiency, various aspects of the PV/T system's performance were evaluated to assess its overall efficiency. The results were compared with the findings by Abdullah *et al.*, [34]. Figure 5 shows the results of thermal efficiency of the PV/T system using GNP nanofluids are generally higher compared to using distilled water across various flow rates and irradiances with the maximum η_{th} achieved is 80% at 80 L/hr and 800 W/m² while the minimum η_{th} achieved is 28% at 20 L/hr and 200 W/m². The utilization of GNP nanofluids in the PV/T system shows a consistently higher thermal efficiency at all flow rates compared to the traditional working fluid. This shows that adding GNP nanofluids to the system improves its thermal performance and ultimately improves the system's ability to convert solar energy into heat. The PV/T system's thermal efficiency is improved by higher nanoparticle concentrations due to increase in thermal conductivity of nanofluids. Increased flow rates result in better heat transfer between the fluid and the PV panel [35]. The panel temperature drops, and thermal efficiency rises as more fluid moves through the system and has the capacity to absorb more heat. As the flow rate increases, the fluid spends less time in the collector, resulting in a smaller temperature rise [36].

The system can capture more energy in the form of heat and electricity when the solar irradiance is higher [37]. Heat transfer is improved by the fluid's and absorber plate's increasing temperature

differential. Additionally, this might raise the fluid's temperature, which would enhance thermal energy use. There is a significant increment of η_{th} at 60 L/hr and 600 W/m² where this is due to the temperature-dependent properties of the GNP nanofluids. Temperature can alter the thermal characteristics of nanofluids, which can impact performance under various operating circumstances [38].

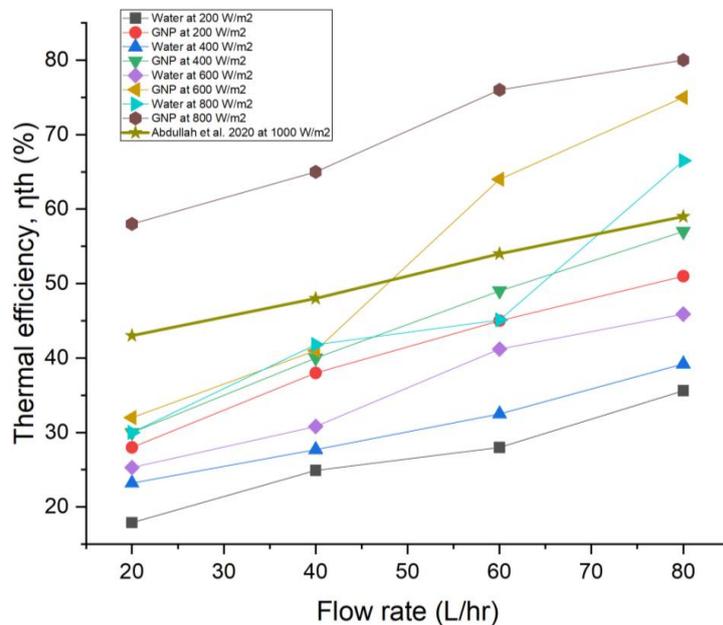


Fig. 5. Thermal efficiency of PV/T system using 0.6 wt.% GNP nanofluids

3.2.2 Electrical efficiency

In the context of electrical efficiency, Figure 6 indicates that electrical efficiency increased in tandem with a rise in flow rate where the system achieved the highest electrical efficiency of 8.9% at 80 L/hr and 800 W/m² compared to 8.8% achieved by water. The lowest electrical efficiency achieved by the system utilizing the GNP nanofluid is 8% at 20 L/hr and irradiances of 200 W/m² and 400 W/m². The nanofluid is more effective than water in every irradiance. These findings imply that improving the nanoparticle content of the nanofluid formulation increases the electrical efficiency of the PV/T system. It can be concluded from the results that nanofluid can absorb heat throughout the system. Solar energy can be converted into electrical power more successfully due to nanofluid's superior electrical efficiency compared to water due to its efficient absorption and dispersion of heat [39]. On the other hand, higher electrical efficiency is observed at 60 L/hr for the PV/T system at 400 W/m² irradiance as opposed to 600 and 800 W/m². The reason behind this is that the PV cells may get less heated at lower irradiance levels, allowing the nanofluid to cool the cells and preserve their efficiency more successfully. The PV cells get hotter under higher irradiance levels, which lowers their electrical conversion efficiency. Lower electrical efficiency than in the 400 W/m² case results from the nanofluid's inability to adequately cool the cells at these higher irradiance levels [40].

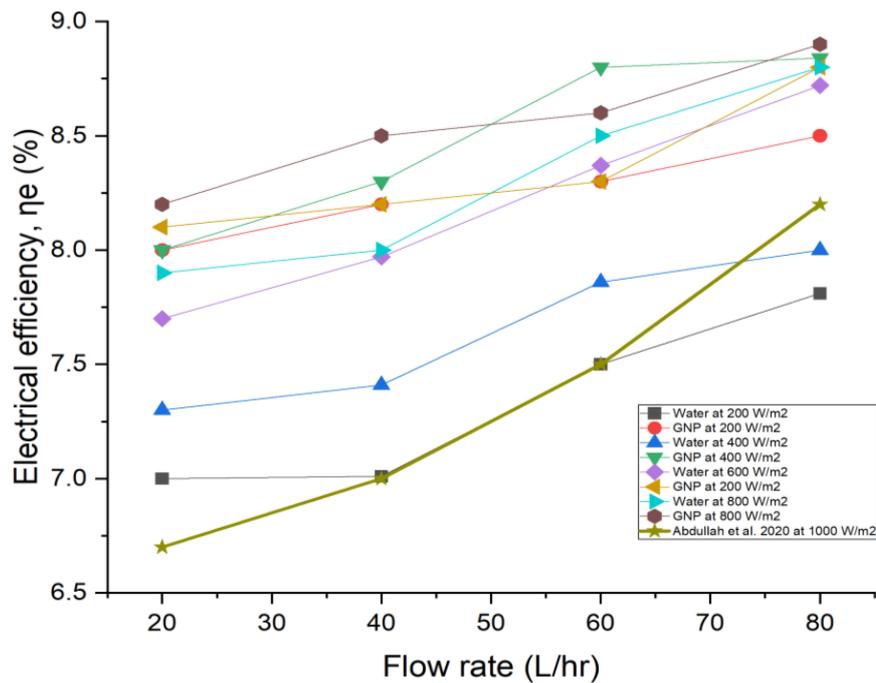


Fig. 6. Electrical efficiency of PV/T system using 0.6 wt.% GNP nanofluids

Figure 7 illustrates the relationship between electrical efficiency and I-V curves of the PV/T system under varying solar irradiance levels, comparing GNP nanofluids with water as the working fluids. Across all irradiance levels, the I-V curves exhibit similar trends, with increased flow rates resulting in higher short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}). This indicates improved cooling efficiency at higher flow rates, which lowers the PV cell temperatures and enhances electrical performance. Notably, the increment in electrical efficiency diminishes at higher flow rates, as the performance difference between 60 L/hr and 80 L/hr is less significant than that observed at lower flow rates.

For all flow rates, the GNP nanofluid exhibits slightly higher I_{sc} and V_{oc} compared to water, suggesting superior cooling capabilities due to its enhanced thermal properties. The I-V curves for GNP nanofluid also show a more rectangular shape, indicating a higher fill factor (FF). This suggests improved overall electrical performance, likely due to more uniform cooling and reduced hot spots on the PV surface [41]. Additionally, the maximum power point (MPP) for GNP nanofluid shifts towards higher voltage values, indicating a higher maximum power output and enhanced electrical efficiency.

The superior performance of GNP nanofluid is evident even at lower flow rates, highlighting its potential advantage in scenarios with limited pumping capacity or where cooling energy consumption needs to be minimized. The consistent improvement across all flow rates shows that GNP nanofluids provide strong and reliable enhancements in electrical efficiency, independent of specific flow conditions. During the experiment, it was observed that at a constant irradiance level, the voltage output of the PV module increased with electrical efficiency, while the current output remained stable within a $\pm 5\%$ error margin. Interestingly, at a specific irradiance level, the current output at 60 L/hr was higher than at 80 L/hr, resulting in better electrical efficiency. This could be attributed to optimal thermal performance at 60 L/hr, where lower flow rates enhance heat transfer effectiveness, reducing PV panel temperatures and improving energy conversion efficiency [42].

The results of the I-V curve indicate that the GNP nanofluid consistently enhances the electrical efficiency of the PV/T system compared to water. The improved cooling performance of GNP nanofluid leads to higher I_{sc} , V_{oc} , and likely better fill factors and MPP values. These enhancements

are evident across different flow rates, showcasing the potential of GNP nanofluids in optimizing PV/T system performance.

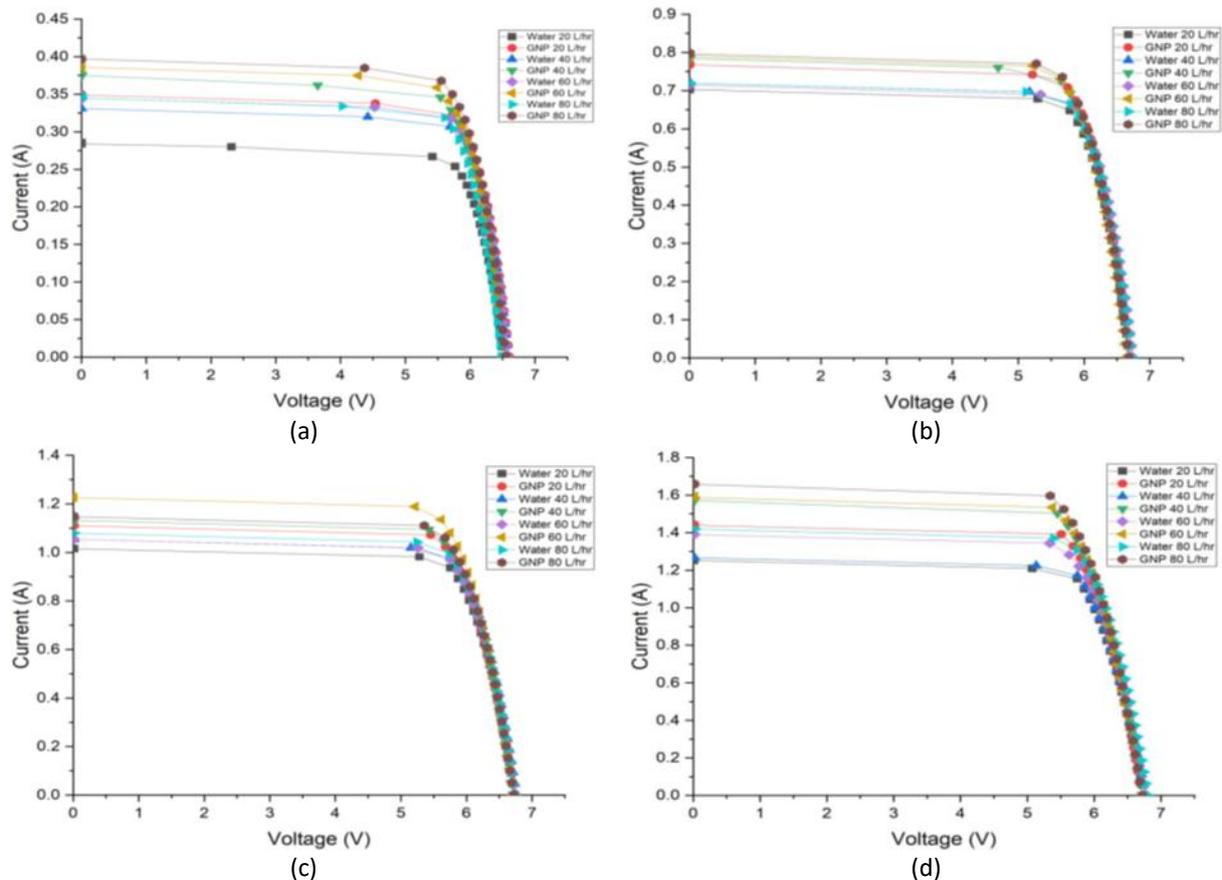


Fig. 7. I-V curve comparison between 0.6 wt.% GNP nanofluid and distilled water at different irradiance (a) 200 W/m² (b) 400 W/m² (c) 600 W/m² (d) 800 W/m²

3.2.3 Overall efficiency

As in Figure 8, it shows that GNP/water nanofluids exhibit better overall efficiency compared to distilled water as the solar irradiance and flow rate increased with the highest overall efficiency achieved is 88.9% at 80 L/hr and 800 W/m² using GNP nanofluid compared to water with overall efficiency of 75.3% at the same flow rate and irradiance along with the overall enhancement of 17%. The nanofluid enhanced the system's thermal performance by maximizing heat utilization and minimizing heat losses through efficient heat absorption and transfer [43,44]. A more effective conversion of solar energy into electrical power was made possible by the nanofluid's higher electrical efficiency. This increased electrical efficiency, which was correlated with high thermal efficiency, helped the GNP nanofluid-based PV/T system achieve a higher overall efficiency.

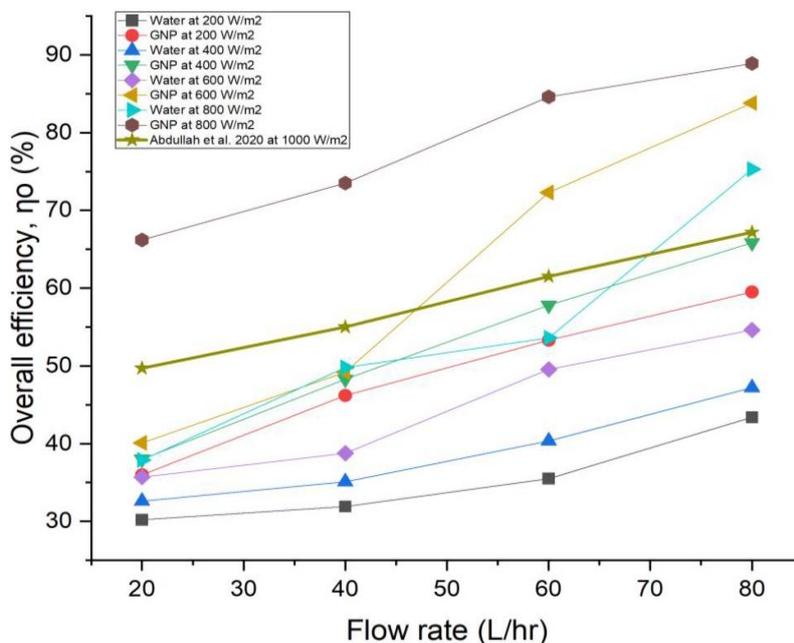


Fig. 8. Comparison of overall efficiency of PV/T system using GNP nanofluids and distilled water at various flow rate and irradiance

3.2.4 Statistical analysis

A comprehensive statistical analysis was conducted to validate the study's claims regarding the performance enhancements achieved using GNP nanofluids compared to distilled water. The effects of three parameters which are the flow rate, irradiance and type of fluid that directly affect the thermal and electrical efficiency of the PV/T system are investigated using response surface method (RSM).

The significance of the results was examined by applying analysis of variance (ANOVA). The ANOVA table represents the sum of squares, mean squares, and degree of freedom of the model. Table 2 and Table 3 presented the statistical analysis results of the regression model expressing the thermal and electrical efficiency of the PV/T system where A represents the fluid flow rate, B is solar irradiance and C is type of fluid.

The ANOVA confirms that the model is statistically significant, where in Table 2, the F-value of the model developed for the thermal efficiency of the PV/T system is 63.60 and the p-value is <0.0001. These results indicate that the model is reliable. The ANOVA also reveals the significant contribution of each variable where the flow rate was found to be highly significant, with the largest contribution to thermal efficiency improvements. The irradiance is also highly significant, reflecting the critical role of solar intensity. The type of fluid used is statistically significant, demonstrating the superior thermophysical properties of GNP nanofluids compared to distilled water. Additionally, the interaction effects of the variables were found significant, indicating synergistic effects that contributed to overall thermal efficiency.

In Table 3, the ANOVA results confirm that the developed response surface model for electrical efficiency is highly significant, with a model F-value of 65.74 and a p-value is <0.0001. This indicates a strong predictive capability of the model and the variations in electrical efficiency are not due to random noise. This also indicates a strong relationship between the variables and the response.

Table 2
 ANOVA table for thermal efficiency of PV/T system

Source	Sum of squares	df	Mean square	F-value	p-value
Model	8297.20	8	1037.15	63.60	<0.0001
A	2967.26	1	2967.26	181.96	<0.0001
B	2549.05	1	2549.05	156.31	<0.0001
C	2336.03	1	2336.03	143.25	<0.0001
A ²	0.66	1	0.66	0.040	0.8425
B ²	185.23	1	185.23	11.36	0.0026
AB	80.71	1	80.71	4.95	0.0362
AC	63.72	1	63.72	3.91	0.0602
BC	114.53	1	114.53	7.02	0.0143
Residual	375.07	23	16.31		
Cor Total	8672.28	31			

Table 3
 ANOVA table for electrical efficiency of PV/T system

Source	Sum of squares	df	Mean square	F-value	p-value
Model	7.73	6	1.29	65.74	<0.0001
A	2.80	1	2.80	142.60	<0.0001
B	1.78	1	1.78	90.94	<0.0001
C	2.36	1	2.36	120.37	<0.0001
AB	0.0093	1	0.0093	0.4752	0.4970
AC	0.0605	1	0.0605	3.08	0.0913
BC	0.7250	1	0.7250	36.98	<0.0001
Residual	0.4901	25	0.0196		
Cor Total	8.22	31			

The regression analysis further supports the findings, providing mathematical models that predict thermal efficiency based on the input factors where the relationship between the efficiency of the PV/T system and the variables is given in Eq. (7) and Eq. (8) which shows the mathematical model for thermal and electrical efficiency of the PV/T system using GNP nanofluids, respectively.

$$\eta_{th} = 23.62531 + 0.29907A - 0.027655B + 3.58594 \times 10^{-4}A^2 + 6.01484 \times 10^{-5}B^2 + 3.17638 \times 10^{-4} \quad (7)$$

$$\eta_e = 7.73906 + 9.56875 \times 10^{-3}A + 2.11875 \times 10^{-4}B + 3.41250 \times 10^{-6}AB \quad (8)$$

where A represents the flow rate and B is the irradiance.

The regression equation emphasizes the strong linear contributions of flow rate, irradiance, and fluid type. In terms of actual factors, the model predicts higher thermal and electrical efficiency for GNP nanofluids compared to distilled water. This outcome aligns with experimental results and highlights the value of GNP nanofluids for enhanced heat transfer and energy conversion.

The R² values of the created models are shown in Table 4. The R² values of the models developed for thermal and electrical efficiency of the PV/T system are close to 100 which are 95.68% and 94.04%, respectively, and these results indicate that the models are eligible for use in calculations of efficiency. The R²_{adj} value is another statistical comparison method where the value is also close to 100 indicates that the mathematical models developed lead to a good correlation between the independent and dependent variables.

Table 4

Response	R^2	R^2_{adj}	R^2_{pred}
Thermal efficiency	0.9568	0.9417	0.9021
Electrical efficiency	0.9404	0.9261	0.9144

A clear and quantitative foundation for comparing the fluids used is provided by the statistical analysis, which shows that GNP nanofluids continuously outperformed distilled water in terms of thermal and electrical efficiency across a range of flow rates and irradiance levels. These methods validate the enhancements achieved by using GNP nanofluids, providing evidence that the observed improvements are not random but are statistically significant.

3.2.5 Analysis of efficiency enhancement and heat transfer improvement

The comparative analysis of thermal and electrical efficiency in PV/T systems utilizing GNP nanofluids and distilled water demonstrates notable improvements in system performance. The use of GNP nanofluids significantly enhances thermal efficiency, which can be attributed to their superior heat transfer properties. These nanofluids facilitate more effective absorption and utilization of solar energy for heat generation, outperforming water as a working fluid.

While electrical efficiency trends may vary, the observed overall efficiency highlights the potential of nanofluids to optimize electrical performance. By maintaining lower operating temperatures and improving thermal management, nanofluids help mitigate thermal degradation of photovoltaic cells, thus contributing to enhanced electrical output [45].

Regarding heat transfer enhancement, GNP nanofluids offer distinct advantages due to their high thermal conductivity and superior heat transfer capabilities. These properties enable more efficient heat transfer within the PV/T system, reducing thermal losses and improving the heat dissipation from photovoltaic cells [46]. To further support the statement, Alshaheen *et al.*, [47] reported overall efficiency improvements of up to 9.46% when MWCNT nanofluids were employed, and Diwania *et al.*, [48] reported that Fe/water nanofluids showed an increment of 9.84% in PV/T systems, whereas the current study observed a 17% enhancement with GNP nanofluids under similar conditions. This optimization leads to better thermal management and supports improvements in both thermal and electrical efficiency.

The integration of GNP nanofluids into PV/T systems creates synergistic benefits by simultaneously boosting thermal and electrical efficiency while enhancing heat transfer processes. This dual improvement ensures a more effective utilization of solar energy resources, emphasizing the importance of nanofluid technology in optimizing PV/T system performance. The findings highlight the holistic performance enhancement achieved through the adoption of nanofluid-based cooling, providing a pathway for more efficient and sustainable energy solutions.

4. Conclusions

The performance analysis of photovoltaic thermal (PV/T) systems using graphene nanoplatelets (GNP) water-based nanofluids as the working fluid is crucial for optimizing their efficiency and sustainability. PV/T systems are designed to harness both electrical and thermal energy from solar irradiance, making them a promising alternative to traditional energy sources. The results show that the GNP/water nanofluids gives better thermal and electrical efficiency towards the PV/T system compared to distilled water with the highest thermal and electrical efficiency obtained was 80% and 8.9%, compared to water, 66.5% and 8.8%, respectively, along with the overall enhancement of 17%.

It has the potential to outperform traditional water-based systems in terms of thermal and electrical efficiency under certain heat transfer conditions. It was evident that the nanofluid could boost energy conversion and system efficiency because of its increased thermal and electrical efficiency. The superior thermal properties of GNP nanofluids likely contribute to improved heat transfer rates and energy conversion processes within the PV/T system, highlighting the benefits of utilizing nanofluid technology for enhancing the performance of renewable energy systems.

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Author Contributions

The authors confirm contribution to the paper as follows: experiment and data collection: Nurul Izzati Akmal Muhamed Rafaizul, Mohd Afzanizam Mohd Rosli; analysis and interpretation of results: Mohd Afzanizam Mohd Rosli, Poppy Puspitasari, Avita Ayu Permanasari, Norli Abdullah; review manuscript preparation: Azrin Hani Abdul Rashid, Faridah Hussain; data arrangement: Nurul Izzati Akmal Muhamed Rafaizul, Safarudin Gazali Herawan.

Data Availability

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