OPTIMIZING SOLAR OUTPUT TO REDUCE PHOTOVOLTAIC PANEL NUMBER IN IRRIGATION

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ABSTRACT

This experiment aimed to study the effect of integrating a passive cooling system with varying air passage outlet clearances: 0 cm (C0, control), 10 cm (C1), 15 cm (C2), and 20 cm (C3) on the performance of polycrystalline and monocrystalline PV panels used in solar-powered irrigation systems. Performance metrics included PV efficiency, maximum power, required number of panels, and operational costs. Results showed a highly significant effect ($P < 0.0001$) of air passage clearance and PV type on all measured parameters. Specifically, the 10 cm clearance (C1) yielded the best outcomes, achieving the highest PV efficiency (16.26%), maximum power (41.12 W), lowest panel number (7), and lowest operational cost ($8.75). Among panel types, polycrystalline panels demonstrated superior efficiency (12.52%), maximum power (32.05 W), required fewer panels (11), and incurred lower operational costs ($13.50) compared to monocrystalline panels. These findings indicate that optimizing passive cooling can significantly enhance PV performance while reducing system size and costs.

Keywords: Air passage outlet clearance, number of PV panels, PV operation cost, PV Type.

تحسين إنتاج القدرة الشمسية لتقليل عدد الألواح الكهروضوئية في الري

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المستخلص

هدفت التجربة الى دراسة تأثير إضافة نظام تبريد سلبي بخلوص مخرج هواء مختلف: 0 سم (كمعاملة مقارنة), 10سم, 15 سم, 20 سم على اداء الألواح الكهروضوئية المتعددة وألاحادية التبلور والمستخدمة في أنظمة الري التي تعمل بالطاقة الشمسية. شملت مؤشرات الاداء كفاءة الألواح, اقصى قدرة, عدد الالواح المطلوبة و تكاليف التشغيل. اظهرت النتائج تاثير معنوي عالي جدا لكل من خلوص مخرج الهواء ونوع الألواح الكهروضوئية على جميع المعايير المقاسة. اذ حقق الخلوص الاول 10 سم أفضل النتائج، حيث سجل أعلى كفاءة للألواح الكهروضوئية 16.26% ، وأعلى قدرة 41.12 واط، وأقل عدد من الألواح 7، وأقل تكلفة تشغيل 8.75 دولار. أما من حيث نوع الألواح، فقد حققت الألواح متعددة التبلور اعلى كفاءة 12.52%، واقصى قدرة 32.05 واط، و أقل عدد للالواح 11، مع اقل تكلفة تشغيل 13.50 دولار مقارنة بالالواح الاحادية التبلور. اوضحت النتائج أن إضافة التبريد السلبي يمكن أن يحسن أداء الالواح الكهروضوئية مع تقليل حجم منظومة الري وتكاليف التشغيل.

الكلمات المفتاحية: خلوص مخرج ممرالهواء , عدد الالواح الكهروضوئية , تكاليف تشغيل اللوح الكهروضوئي, نوع اللوح الكهروضوئي.

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INTRODUCTION

Solar-powered irrigation systems have emerged as promising solutions to withstand the increase in global energy demand and the pressing need for sustainable agricultural practices. In recent years, Iraq has increasingly adopted solar-powered irrigation systems to address the significant lack of precipitation affecting its agriculture (6, 23). This transition is strongly supported by the country's abundant sunlight and intense solar radiation (2, 5, 31). However, the efficiency of photovoltaic (PV) panels, which are crucial components of these systems, is significantly affected by high ambient temperatures, leading to decreased performance and increased costs.Practically, numerous external factors can influence the output of PV panels, including incident solar radiation levels, ambient temperature, weather conditions, panel tilt angle, and load conditions. Solar panels are typically rated at a specific insolation level (1000 W/m²) and a designated temperature (25Cº) (13, 14, 23). Amelia et al. (7) stated that PV panel operation temperature is considered one of the most important factors that can significantly affect any PV panel's performance through its effect on solar cell-produced voltage. High temperatures adversely impact the performance of PV panels (9, 12, 32). PV modules can only convert a small fraction of solar radiation, about 13 - 20%, into electricity (8), while the rest will be converted to heat (16, 25), and this can be affected by ambient temperature (19). The accumulation of heat energy from absorbed solar irradiance increases the panels' operating temperature, leading to reduced panel output (17, 34, 35). Low conversion efficiency is one of the challenges associated with PV panels. Typically, a high portion of solar energy, over 75%, absorbed by the panel is transformed into heat, which raises the panel's temperature and significantly reduces its efficiency and power output (22, 30, 33). Using cooling methods can reduce PV panel temperatures by 14–20%, resulting in a 9% increase in efficiency and improved maximum power output (11, 15, 26, 27). Zeinaldeen (37) demonstrated that an effective cooling system can significantly improve the fill factor, efficiency, and maximum power of photovoltaic (PV) panels by reducing their operating temperature (24). Ali (4) repoted that monocrystalline panels was highly sensitive to high ambient temperature comparing with plycrystalline during summer in hot regions like Iraq. She proposed cooling solutions, such as air or water, to mitigate performance losses. Pomares-Hernández et al. (29) clarified that air currents passing over solar panels play a crucial role in natural (passive) convection models, serving as an efficient method to reduce their elevated temperatures and consequently enhance their performance (3, 36). Parthiban et al. (28) showed that various techniques have been employed by researchers to reduce the temperature of PV panels. The majority of these techniques were effective in enhancing the output of the PV panels (10, 20). Solar irrigation systems can utilize solar power to operate solar pumps, reducing reliance on fossil fuels, improving water availability, and reducing the overall operation costs while using an environmentally friendly source of energy (1). Improving solar panel performance can influence the performance of solar irrigation pumps. Operation temperature, solar radiation, and PV maximum voltage are crucial parameters for enhancing the efficiency of solar PV water pumps. (32, 35).

Research Question: How will adding a passive cooling system to the PV panels affect their performance during the hottest months of the year, and how will that impact the required number of PV panels for the solar irrigation system and PV operational costs?

Research Objectives: To evaluate PV efficiency and output with different airflow clearances and analyze how passive cooling impacts performance, panel count, and costs.

MATERIALS AND METHODS

An experiment was conducted during July and August 2024 at a site in Baghdad, Iraq (Latitude: 33°18′55″N, Longitude: 44°21′58″E) to study the effect of using different passage outlet clearances and different PV panel types to improve solar irrigation pump performance by reducing PV panels number. PV efficiency, maximum power, required PV panel number, and PV operational costs were determined. Two factors were used: The first factor included different air-cooling outlet clearance with four levels: 0 Cm (C0 = Control treatment – without air flow passage), 10 Cm (C1), 15 Cm (C2), and 20 Cm (C3), while second factor was PV type with two levels which included Polycrystalline and Monocrystalline panel. Each experiment treatment was repeated six times daily every 30 minutes, from 12:00 pm until 2:30 pm during the hottest days in July and August. The average ambient temperature for the experiment site was (121.6° F, 49.8°C), while the average humidity was (36.1%).

Monocrystalline PV panel has an optimal power (Pmax): 50 Watt, maximum voltage (Vmax): 18V, maximum current (Imax): 2.7A, open circuit voltage (Voc): 20V, and short circuit amperage (Isc): 2.9A. Polycrystalline PV panel has an optimal power (Pmax): 50 Watt, maximum voltage (Vmax): 18V, maximum current (Imax): 2.78A, open circuit voltage (Voc): 22V, and short circuit amperage (Isc): 2.97A. A solar irrigation pump (LSPI-12-20-2.5-200-1) with a power (200W) and Max flow (2.5 m³/h.) was used. PV performance was analyzing during the experiment using the solar module analyzer (PROVA-200). The incident solar radiation was measured using the solar power meter (TES 132). The panels temperature was measured using the temperature sensors (TMC-2000) which was placed at the backside of the panels. All the panels faced south with a tilt angle of 33° from horizontal (57° from vertical) (13). An airflow passage was built to be attached to the back side of the panel with fixed inlet clearance (25 Cm) and adjustable outlet clearance (Fig. 1).

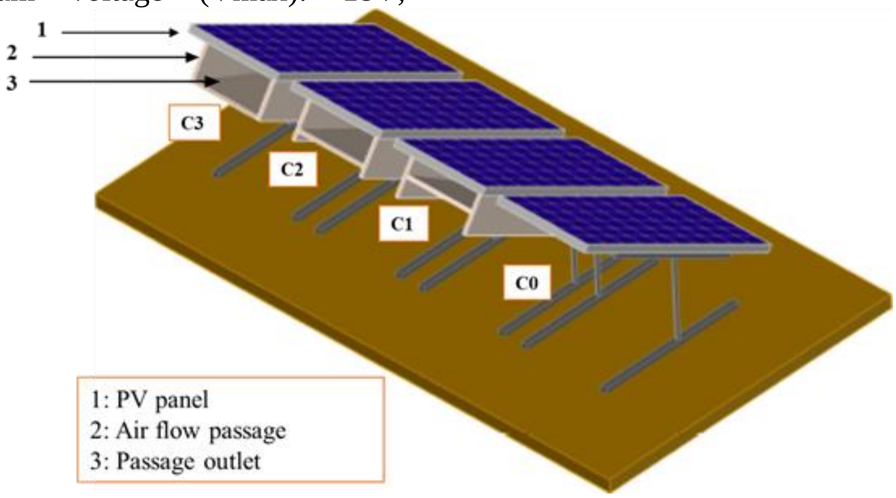


Figure 1. PV panels with the adjustable outlet clearances

The dependent variables (responses) identified in this experiment are as follows:

PV efficiency (%):

The PV panel efficiency is the percentage of the power that the PV panel can produce compared to the power it can receive. Hatwaambo et al. (21), Equation (1):

$$\eta = \frac{FF \cdot I_{SC} \cdot V_{oc}}{I_N \cdot A} \qquad (1)$$

η : PV panel efficiency (%).

FF: PV panel fill factor.

I_{SC} : The short-circuit current (Amps).

V_{OC} : The open-circuit voltage (Volt).

I_N : The incident solar radiation on the solar cell module (Watt/m²).

A: The actual active area of the solar cell module (m²).

The maximum Power (Watt).

It can be defined as the maximum power that the PV panel can produce (37), Equation (2):

$$P_{max} = I_{max} \cdot V_{max} \qquad (2)$$

P_{max}: The panel maximum power (Watt).

I_{max} : The panel maximum current (Amps).

V_{max} : The panel maximum voltage (Volts).

Number of required PV panels

It represents the number of panels required to run the solar pump, Equation (3):

$$N = \frac{P_{Pump}}{f \cdot P_{max}} \qquad (3)$$

N: Number of required PV panels.

P_{Pump}: The maximum power of the solar pump (Amps).

f : Performance improvement factor.

PV operation Cost ($)

It represents the power cost multiplied by the number of PV panels for the system, Equation (4):

$$PV_{OC} = \frac{PV_{IC}}{PV_{TP}} * N \qquad (4)$$

PV_{OC}: PV panel operation Cost ($).
PV_{IC}: PV panel initial cost ($).
PV_{TP}: PV panel theoretical power (watt).

Research objectives

The objectives of this research are to optimize solar irrigation systems by maximizing PV panel output and minimizing the number of panels required. This will be achieved by studying the impact of air passage outlet clearances on different PV panel types and their effects on PV performance during July and August 2024.

Statistical analyses

All statistical analyses were performed using IBM SPSS Statistics (Version 27) (18). Data were evaluated using two-way ANOVA (RCBD, α = 0.05). Dunnett's test compared control vs. other treatments, while Tukey's test compared treatments within each factor. Significance was set at $P < 0.05$; $P > 0.05$ and ≤ 0.1 indicated marginal significance (Tables 1–4). Pearson correlation assessed linear relationships among PV efficiency, maximum power, required panel number, and operation cost (Table 5).

RESULTS AND DISCUSSION

The PV efficiency (%): Table (1) shows the two-way analysis of variance results for PV type and outlet clearance and their interactions on PV panel efficiency (%). There is a highly significant effect for air passage outlet clearance ($F_{(3,568)} = 768.859$, $P < 0.0001$) and a highly significant effect for PV type ($F_{(1,568)} = 24.806$, $P < 0.0001$) on PV panel efficiency (%). Furthermore, Table (1) demonstrates that the interaction between outlet clearance and PV type has a significant influence on PV panel efficiency (%) ($F_{(3,568)} = 0.940$, $P = 0.421$). Based on the sum of squares values, the air passage outlet clearance has the largest effect on panel efficiency (%), followed by the PV type (31).

Table 1. Two-way analysis of variance results for PV type and outlet clearance on PV panel efficiency (%).

Source	df	Sum of Squares	Mean Square	F	Sig.
Outlet Clearance	**3**	**10647.534**	**3549.178**	**768.859**	**0.000**
PV type	**1**	**114.508**	**114.508**	**24.806**	**0.000**
Outlet Clearance: PV type	**3**	**13.019**	**4.340**	**0.940**	**0.421**
Error	**568**	**2621.981**	**4.616**		
Total	**575**				

Figure (2a) interprets that the air passage outlet clearance significantly affects PV efficiency. The highest average efficiency (16.26%) was with C1, followed by C2 (14.66%) and C3 (12.34%), while the control had the lowest results (5.03%). The 10 cm clearance (C1) likely accelerates airspeed, reduces panel temperature, and enhances both short circuit amperage and open circuit voltage, thereby increasing PV efficiency. Figure (2b) illustrates that the PV type has a highly significant effect on panel efficiency. Polycrystalline panels had the highest average efficiency (12.52%), while monocrystalline panels had the lowest (11.62%), likely due to polycrystalline panels' superior heat resistance.

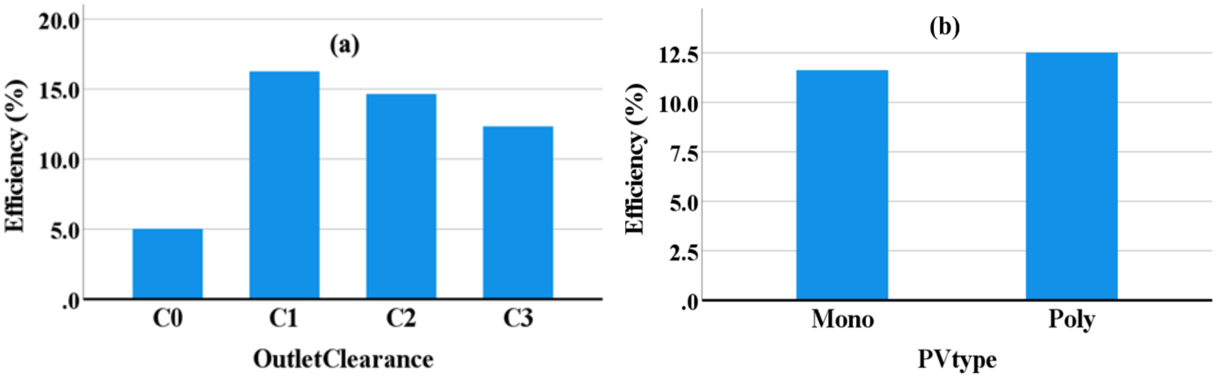


Figure 2. The effect of air passage outlet clearance and PV type on PV efficiency (%).

Figure (3) illustrates that the two-way interaction between the PV type and air passage outlet clearance on PV efficiency was highly significant (P < 0.0001). The highest panel efficiency (16.91%) was achieved by the polycrystalline panel with first outlet clearance (C1), while the lowest results (11.81%) were achieved by monocrystalline panel with the third clearance (C3).

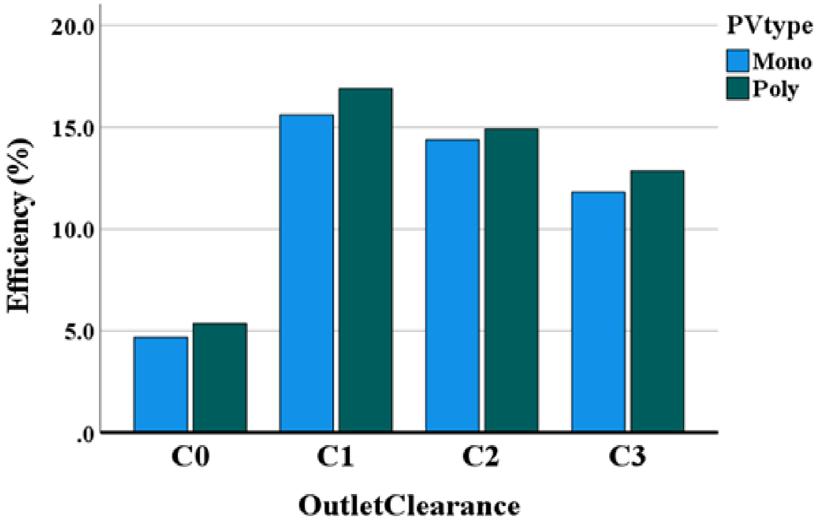


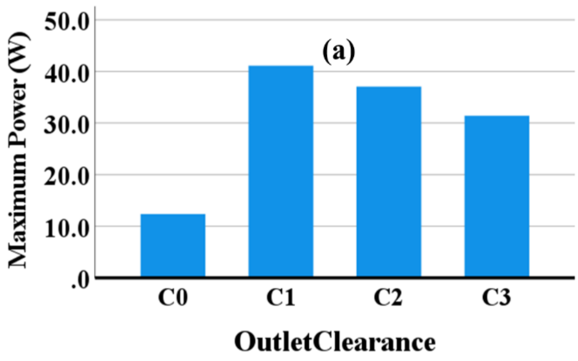
Figure 3. Effect of the interaction between PV panel type and outlet clearance on PV efficiency (%).

The PV maximum Power (W): Table (2) shows the two-way analysis of variance results for PV type and outlet clearance and their interactions on PV panel maximum power (W). Both air passage outlet clearance ($F_{(3,568)}$ = 575.273, P < 0.0001) and PV type ($F_{(1,568)}$ = 34.363, P < 0.0001) have highly significant effects on PV maximum power (W),while their interaction has a non-significant influence ($F_{(3,568)}$ = 0.201, P = 0.896). Based on the sum of squares values, the air passage outlet clearance has the largest effect on panel efficiency (%), followed by the PV type (31). Figure (4a) demonstrates that air passage outlet clearance significantly impacts PV panel maximum power (W). The highest average power (41.12W) occurred with the first clearance (C1), while C2 and C3 yielded lower averages (37.07W and 31.41W, respectively). The control treatment produced the lowest result (12.37W). This performance difference stems from C1's 10 cm clearance enhancing airspeed, which reduces panel temperature and improves both maximum amperage and voltage, thereby increasing power output.

Table 2. Two-way analysis of variance results for PV type and outlet clearance on PV panel maximum power (W)

Source	df	Sum of Squares	Mean Square	F	Sig.
Outlet Clearance	**3**	**69898.942**	**23299.647**	**575.273**	**0.000**
PV type	**1**	**1391.756**	**1391.756**	**34.363**	**0.000**
Outlet Clearance: PV type	**3**	**24.406**	**8.135**	**0.201**	**0.896**
Error	**568**	**23005.065**	**40.502**		
Total	**575**				

Figure (4b) shows PV type significantly affects maximum power (W). Polycrystalline panels outperformed monocrystalline (32.05W vs 28.94W) due to superior heat tolerance, which enhances voltage and amperage.=



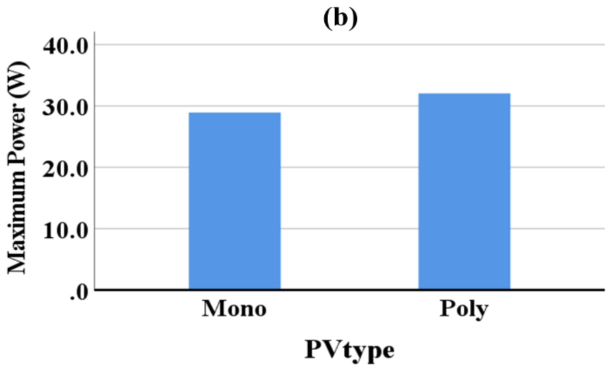


Figure 4. The effect of air passage outlet clearance and PV type on PV maximum power (W).

Figure (5) illustrates that the two-way interaction between the PV type and air passage outlet clearance on PV maximum power was highly significant (P < 0.0001). The highest panel maximum power (42.81W) was achieved by the polycrystalline panel with the first outlet clearance (C1), while the lowest result (29.78W) was achieved by the monocrystalline with the third clearance (C3).

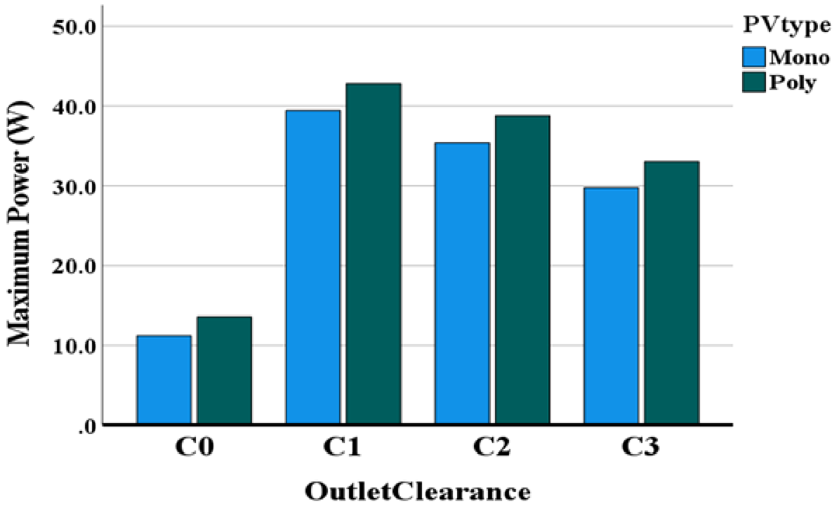


Figure 5. Effect of the interaction between PV panel type and outlet clearance on PV maximum power (W). ***Number of required PV panels***

Table (3) shows the Two-way analysis of variance results for PV type and air passage outlet clearance and their interactions with the number of required PV panels. There is a highly significant effect for air passage outlet clearance ($F_{(3,568)}$ = 457.784, P < 0.0001) and a highly significant effect for PV type ($F_{(1,568)}$ = 5.742, P < 0.017) on the number of required PV panels. Furthermore, Table (3) illustrates that the interaction between outlet clearance and PV type has a significant influence on the number of required PV panels ($F_{(3,568)}$ = 1.104, P < 0.005).

Table 3. Two-way analysis of variance results for PV type and outlet clearance on the number of required PV panels

Source	df	Sum of Squares	Mean Square	F	Sig.
Outlet Clearance	**3**	**11304.269**	**3768.090**	**457.784**	**0.000**
PV type	**1**	**47.266**	**47.266**	**5.742**	**0.017**
Outlet Clearance: PV type	**3**	**27.255**	**9.085**	**1.104**	**0.347**
Error	**568**	**4675.292**	**8.231**		
Total	**575**				

Figure (6a) shows that the air passage outlet clearance has a significant effect on the PV panel number. The lowest panel number mean achieved by the first outlet clearance (C1) was (6.97) PV panels, while both of the clearances (C2 and C3) had a PV number mean of (8.08, 10.79), respectively. The highest PV number to run the solar pump (18.33) panels was achieved by the control treatment C0. Figure (6b) shows PV type significantly impacts the required panel number. Polycrystalline panels needed fewer units (mean 10.75) than monocrystalline (mean 11.33), likely due to better heat resistance. Adding the air flow passage to the back of the panels also boosts voltage and amperage, reducing the total panels needed for solar irrigation pumps.

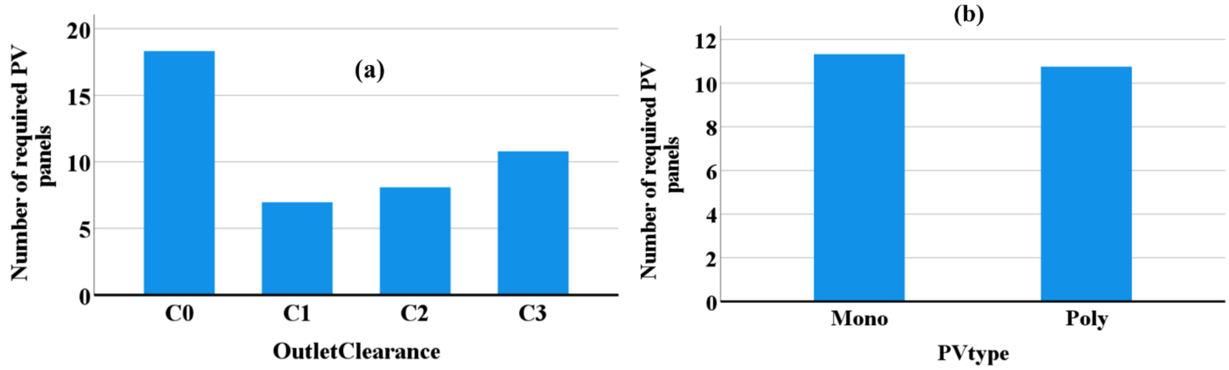


Figure 6. The effect of air passage outlet clearance and PV type on the number of required PV panels.

Figure (7) illustrates that the two-way interaction between the PV type and air passage outlet clearance on PV number was highly significant (P < 0.0001). The lowest results (6.76) panels was achieved by polycrystalline with the first clearance (C1), while the highest PV required number (10.90) panels was achieved by the monocrystalline panel with third outlet clearance (C3)

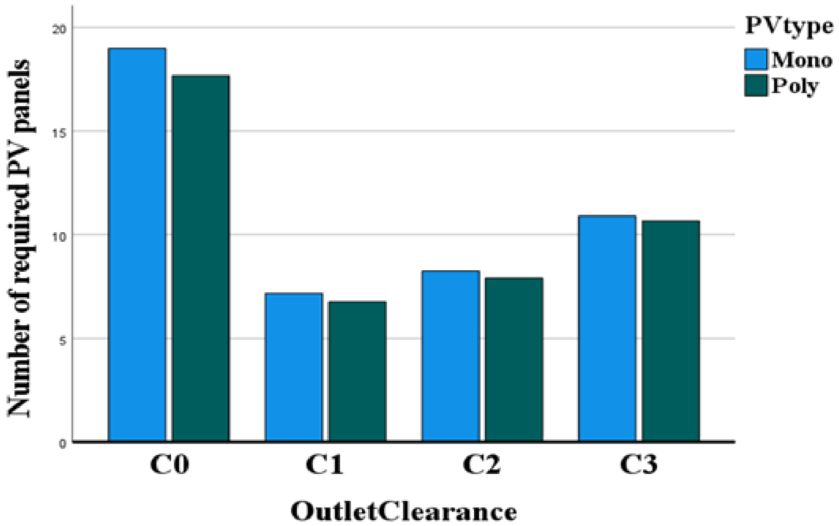


Figure 7. Effect of the interaction between PV panel type and outlet clearance on the Number of required PV panels

PV operation Cost ($)

Table (4) shows the Two-way analysis of variance results for PV type and air passage outlet clearance and their interactions with the PVs operation Cost ($), there was a highly significant effect for air passage outlet clearance ($F_{(3,568)}$ = 461.909, P < 0.0001) and a highly significant effect for PV type ($F_{(1,568)}$ = 4.548, P < 0.033) on the PVs' operation cost. Furthermore, Table (4) demonstrates that the interaction between outlet clearance and PV type has a non-significant effect on the PVs' operation cost ($F_{(3,568)}$ = 0.648, P = 0.585). Figure (8a) shows that the air passage outlet clearance has a significant effect on PVs' operation Cost ($). The lowest PV operation Cost mean achieved by the first outlet clearance (C1) was (8.75$), while both (C2 and C3) had an operation cost mean (10.21$, 13.39$) respectively. The highest operation cost (22.93$) was achieved by the control treatment C0.

Table 4. Two-way analysis of variance results for PV type and outlet clearance on the PVs operation cost ($).

Source	df	Sum of Squares	Mean Square	F	Sig.
Outlet Clearance	3	17555.414	5851.805	461.909	0.000
PV type	1	57.614	57.614	4.548	0.033
Outlet Clearance: PV type	3	24.619	8.206	0.648	0.585
Error	568	7195.849	12.669		
Total	575				

Figure (8b) shows PV type significantly affects operation cost ($). Polycrystalline panels had the lowest mean cost ($13.50) versus monocrystalline ($14.13), likely due to better heat resistance. Airflow passage enhances voltage and amperage, increasing panel's maximum power, reducing operating time, and lowering costs for both panels and the solar irrigation pump.

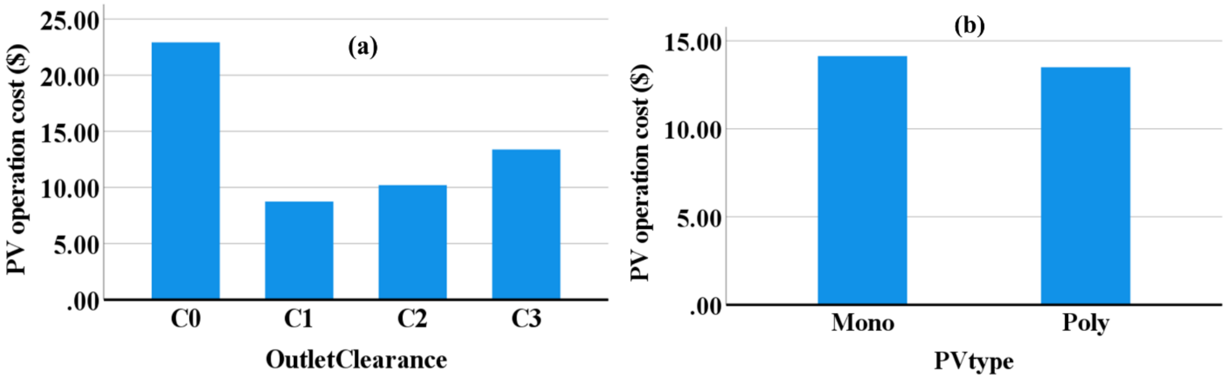


Figure 8. The effect of air passage outlet clearance and PV type on PV operation cost ($).

Figure (9) illustrates that the two-way interaction between the PV type and air passage outlet clearance has a non-significant effect on PVs' operation cost (P = 0.585). The lowest operation cost (8.60$) was achieved by polycrystalline with the first clearance (C1), while the highest cost (13.61$) was achieved by the monocrystalline panel with third outlet clearance (C3).

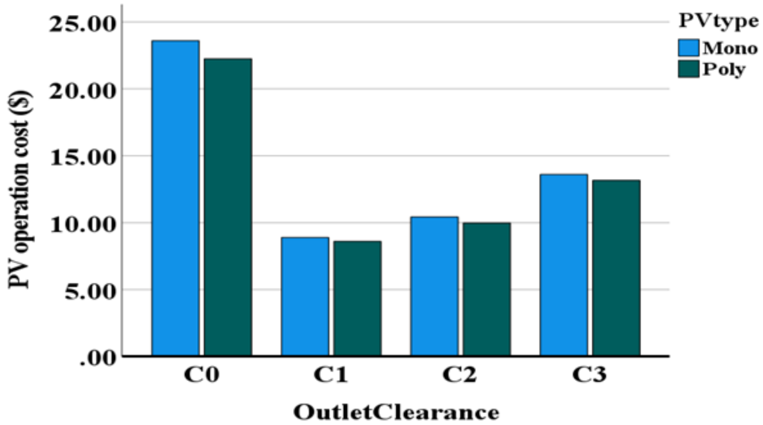


Figure 9. Effect of the interaction between PV panel type and outlet clearance on PVs' operation cost ($)

Dunnett’s test results revealed a highly significant difference (P < 0.0001) between all outlet air passage clearances (C1, C2, C3) and the control (C0) across PV panel efficiency, maximum power, PV required number, and PVs’ operational cost. Tukey’s test also found significant differences among C1, C2, and C3 for each of these parameters.

Table (5) summarizes Pearson correlation coefficients, significance levels, and 95% confidence intervals for relationships among PV efficiency, maximum power, required number, and operation cost. Results show a strong positive correlation between PV maximum power and efficiency (r = 0.981, P < 0.0001), and strong negative correlations between PV maximum power and both required number and operation cost (r = –0.879, P < 0.0001), as well as between efficiency and both required number and operation cost (r = –0.892, P < 0.0001). PV required number and operation cost are perfectly correlated (r = 1.000, P < 0.0001). Thus, increasing PV maximum power and efficiency reduces the required panel number and operation cost.

Table 5. Correlation Coefficients, Significance Levels, and 95% Confidence Intervals for Relationships Among Variables

Variables	Pearson Correlation	Sig. (2-tailed)	95% Confidence Intervals (2-tailed)[a]	
			Lower	Upper
Pmax - Efficiency	0.981	0.000	.978	.984
Pmax - PVnumber	- 0.879	0.000	-.896	-.859
Pmax - OperationCost	- 0.879	0.000	-.896	-.859
Efficiency - PVnumber	- 0.892	0.000	-.907	-.874
Efficiency - OperationCost	- 0.892	0.000	-.907	-.874
PVnumber - OperationCost	1.000	0.000	1.000	1.000

CONCLUSION

This study evaluated the effect of passive cooling on mono- and polycrystalline PV panels using three outlet clearances (10, 15, and 20 cm) compared to a control. Polycrystalline panels with a 10 cm clearance showed the highest performance, making this setup optimal for reducing panel number and costs for solar irrigation systems in hot climates.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DECLARATION OF FUND

The authors declare that they have not received a fund.

JOURNAL DECLARATION

The First author (**Laith. A. Zeinaldeen**) serves as an editor for Iraqi Journal of Agricultural Sciences but was not involved in the peer review process of this manuscript beyond their role as an author. The authors declare no other conflict of interest.

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