Experimental and performance evaluation of the soiling and cooling effect on the solar photovoltaic modules

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Abstract

Solar photovoltaic (PV) system technology is a significant energy source that has no moving parts and can accomplish the desired work with less effort. The technology can help to alleviate the climate change phenomena and achieve sustainable development. One of the most important challenges to address before installing a solar PV system is dirt deposition, e.g., soil/sand/ash. The tiny debris particles accumulate on the top surface of the panel, which decreases the PV conversion efficiency and subsequently lowers the overall performance. This work aims to investigate the effect of soiling deposition (soil, sand, and ash) and surface temperature on the performance of PV modules. In this regard, the fabricated test rig was performed for experimental cleaning and cooling on the top of solar PV modules. Therefore, the module's performance in terms of the current produced, the voltage generated, and module efficiency is evaluated for different dust deposition volumes. The results indicate that the ash affects the PV performance badly, reducing 50 to 60 % of current production for only 50 mL volume, compared to sand and soil. Furthermore, the results also indicated that the efficiency of photovoltaic modules increases by 3-4% when water is used for cleaning and cooling purposes.

Keywords: Solar energy; Soiling accumulation; Photovoltaic module cleaning; Module cooling; Environment conditions.

1. Introduction

Solar energy is a sustainable and natural resource that can be used to produce electricity. Thus, the technology of solar photovoltaic systems has grown rapidly in the recent twenty years; hence, resulting in greater installations of various systems worldwide [1-4]. Notwithstanding, dust deposition is one of the significant issues for solar PV installations. A substantial performance loss was caused as a result of the dust accumulating on the surface of the panels. Thus, a number of researchers studied the soiling accumulation impact on the PV modules performance, experimentally and mathematically [5-9]. Kaldellis et al. [10] developed a scientific approach for modelling to present the impacts of natural air pollution on photovoltaic performance. So, by incorporating empirically collected data into account on the operating parameters of a photovoltaic in urban and other situations at present of air pollutants (i.e., red soil particles, carbonaceous fly-ash and limestone). The findings indicated a significant loss in the photovoltaic energy performance, which is highly reliant on the source and particle composition. The cleanings of the solar photovoltaic systems are currently the more popular soiling mitigation technique. However, the frequency and schedule of cleanings must be tailored to the specific requirements of each location in order to reduce the financial expenses of soiling [11-15].

Mohamed and Hasan [16] adopted a weekly cleaning approach for solar photovoltaic module arrays from February to May. Cleaning the PV module surfaces is a key characteristic that is considered more efficient for recouping power loss. The findings revealed that the loss of energy necessitated weekly cleaning to keep the performance losses at a minimum of 2 - 2.5%. Furthermore, Kalogirou et al. [17] evaluated the impacts of soiling on the performance behavior of three kinds of solar photovoltaic modules of polycrystalline, monocrystalline, and amorphous silicon. The results revealed that artificial soiling on the wet photovoltaics surface significantly impacted the photovoltaic performance. Moreover, Saraei et al. [18] evaluated how the shading, cleaning, and cooling affect the electrical current/power generated via the PV modules. So, the results displayed that the cleaning and cooling of the photovoltaic arrays boost the modules output power by 27% in the non-shading scheme and 34% in the shading scheme of operation. In addition, the cleaning and cooling procedure of PV modules enhanced the output power by 9.5% in the non-shading scheme and 40% in the shading scheme. Al-Addousa et al. [19] assessed the impacts of dust accumulation on the solar photovoltaic plant performance, experimental. The power analysis method is considered to describe the rates of soiling and to scheme the influences on the economic value and the energy yield. Three types of photovoltaic modules were evaluated against dust collection. If cleaning schedules are not followed, energy loss in semi-arid locations might quickly reach up to 10%. It has been demonstrated that different PV technologies perform differently when subjected to higher soiling rates. Tanesab et al. [20] investigated the influence of dust in two geographically distant areas with varied morphologies on the power output deterioration for photovoltaics modules. The performance of the three solar PV modules decreased as the amount of dust on the PV modules surface increased. The consequence of the different systems of dust's transmittance levels began to equilibrium. Also, the various technologies of the photovoltaic modules were shown to have resembling performance deterioration when exposed to various types of dust. Al-Kouz et al. [21] introduced an optimization technique using Extreme Learning Machine (ELM) and Artificial Neural Network (ANN) models to forecast the performance of solar PV systems at various conditions of real dust deposition and environmental temperature. Two models have been conducted to forecast the conversion efficiency of photovoltaic modules as a function of dust deposition and environment temperature with improvement in performance as soon as the cleaning is done manually or by rainfall. The results indicated that predicted learning machine models of PV performance were more accurate in contrast to the optimized artificial neural network model. Konyu et al. [22] made an initial assessment and compared the power loss from PV modules as a result of dust accumulation. According to the results, amorphous silicon photovoltaic modules were affected more than polycrystalline silicon photovoltaic modules.

Alnassera et al.[23] studied the impact of deposition materials such as normal cement, sand, industrial gypsum, and gypsum on the performance of solar photovoltaic modules. In addition, the impact of episodic cleaning and its frequency on photovoltaic module power losses was explored. The analysis found that accumulating these particles on photovoltaic modules decreases transmittance and lowers the resultant power. Chanchangi et al. [24] investigated the effect of soiling on solar photovoltaic panels. A solar simulator and spectrometer have been used to investigate and characterize the impact of the soiling accumulation of 13 different specimens, such as (bird droppings, ash, dust, carpet cement, clay, charcoal, coarse sand, loam soil, laterite, sandy soil, salt, wood dust, and stone dust) on photovoltaic modules performance. Therefore, the results display that charcoal has the worst impaired impact on photovoltaic performance, with up to 98% decrease in short circuit current, although salt appears to have the least influence, with roughly 7% reduction. Moreover, it illustrates that dry accumulation has a lower adherence to the coupons than wet deposition. Moreover, Wu et al. [25] developed a mathematical model that anticipates the effect of dust deposition on PV relative to transmittance depending on the form of dust particles. The results revealed that dust of cubic particles induced a greater reduction in relative transmittance than the dust of spherical particles. Subsequently, When the dust-deposited density is about 10 g/m^2, the relative transmittance due to spherical dust drops from 100% to 77.64%, whereas the relative transmittance due to cubic dust drops to 65.35%. Flowing the layer of water on the top of the solar PV module has changed an incoming perpendicular ray's reflected fraction from about 4.4% to 2.0%. Thus, to keep the panel surface clean, the water decreases the reflection of the incident sunlight by approximately 2- 3.6% and drops the cell temperatures up to 22 °C [26, 27]. Li et al. [28] performed the cooling and cleaning of solar photovoltaic modules to improve their performance. In addition, a modeling investigation of adhesion dust and dissociation was also conducted to determine the airflow rate required to remove the dust particles. The outcomes pertaining to the influence of water droplets on the PV module had a reverse effect, reducing the temperature of the photovoltaic module, which led to a rise in the potential difference and enhanced the output power via at least 5.6% [29]. Hence, as a result of the cooling effect, the power output/efficiency of the module is improved accordingly.

The photovoltaic module's performance is substantially impacted by soiling, which is affected by numerous factors such as weather, site characteristics, surface orientation and tilt angle, dust properties and surface material [24, 30]. Although ambient wind and rainfall are considered natural cleaners, it has been demonstrated that successive dusty winds preceded by scattered showers can significantly impact system performance [31, 32]. For rainless exposure periods of one week, the maximum dust deposition density recorded exceeded 300 mg/m^2, resulting in a 2.1% efficiency reduction [33]. A study demonstrates that performance degradation is 24-43% lower while dust/temperature-associated effects are included, indicating that the direct dust deposit effect is the dominant impact [34]. The various types of solar PV technologies respond in different ways to the negative influence as a result of dust deposition. For example, Ndiaye et al. [35] investigated the electrical performance parameters of crystalline PV modules subjected for one year in a Senegal environment without cleaning. Hence, the result showed that pc-Si modules (18.02 %) than mc-Si modules had a higher power decrease (77.75%).

To the best of authors knowledge, most of the researchers only studied the effect of specific types of soiling on the performance of photovoltaic modules. However, the current research work aims to find the effect of soiling (sand, ash, and soil) and surface cooling for the power and efficiency of solar photovoltaic modules. The research provides insight and a detailed experimental study of how dust accumulation degraded the efficiency of the solar modules and surface cooling increases the performance of the solar modules. The significance of this work is to investigate the impact of soiling on photovoltaic system performance with respect to dust shade and concentration. Furthermore, study the impact of cooling on the solar module to reduce the surface temperature of the photovoltaic cells/modules.

2. Experimental setup

2-1. Fabrication of test rig

This solar photovoltaic module apparatus is fabricated for both cleaning and cooling purposes. The front and side views of the designed system are shown in Fig.1 (a) and (b), respectively. The apparatus consists of a storage tank, upper tank, receiver tank, pump, PV solar panel, pipes, supporting stand, and supports for rotation. The lux meter is used to find the intensity of the sun light, multimeter to calculate voltage and current, and thermocouple to measure the surface temperature of the panel. The pump and solar panel specifications are presented in Tables 1 and 2, respectively. This experiment occurred at the University of Engineering and Technology campus in Lahore, Pakistan.

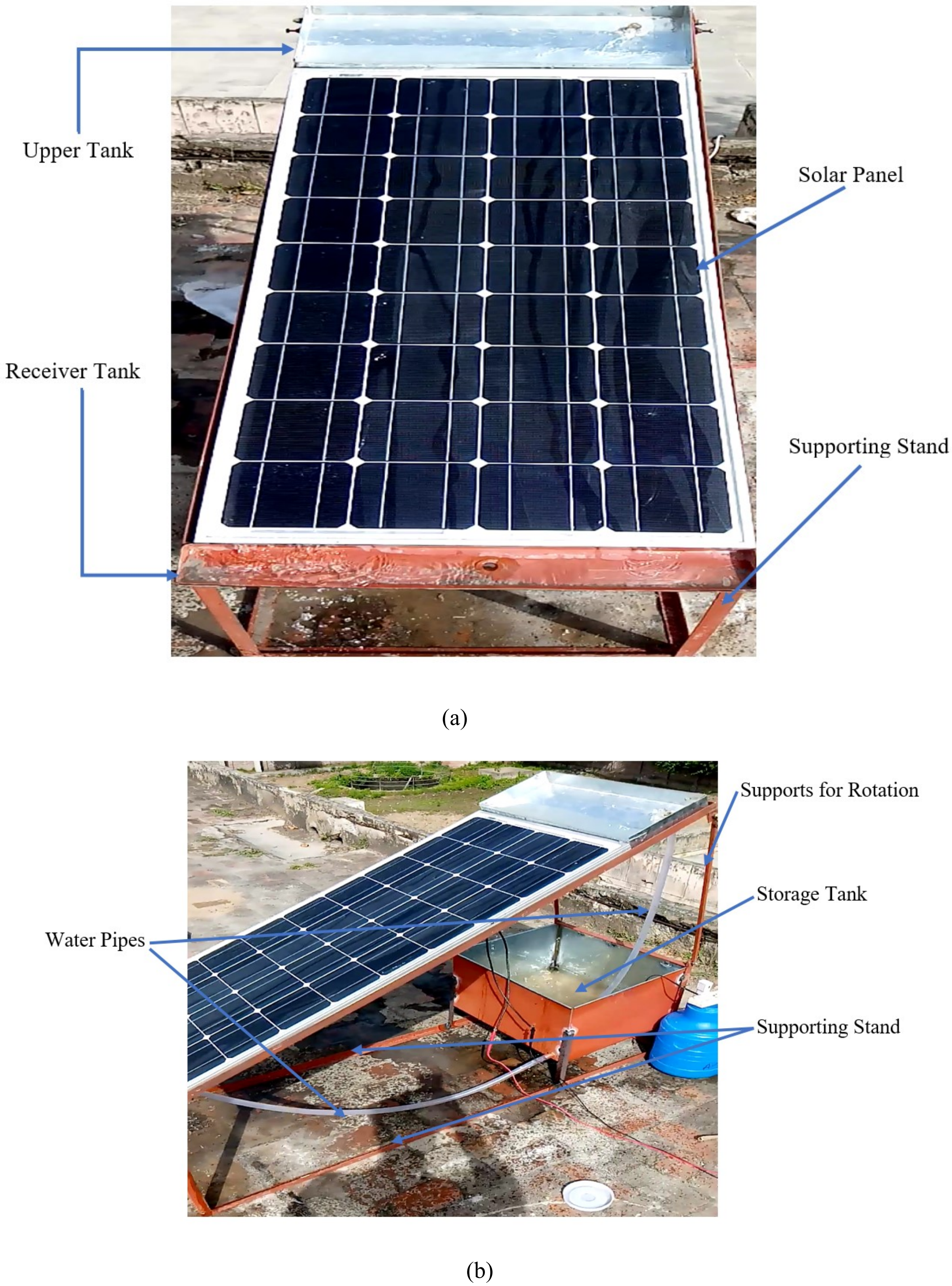

Fig. 1 Fabrication of test rig; (a) front view of the designed system, (b) side view of the designed system.

Table 1 Specification of the water pump.

Description	Characteristics/value
Power	25 W
Maximum flow rate	1000 L/H
Maximum head	2.0 m
Pump type	Submersible

Table 2 Photovoltaic module specification.

Description	Characteristics/value
Model	100M-18
Tolerance	±3%
Rated maximum power (Pm)	100 W
Voltage at Pmax (Vmp)	18.6 V
Open-circuit voltage (Voc)	2204 V
Current at Pmax (Imp)	5.35 A
Short-circuit Current (Isc)	5.73 A
Normal Operating Cell Temperature (NOCT)	47±2 °C
Maximum series rating	10 A
Maximum system voltage	1000 VDC
Operating temperature	-40 °C to +85 °C
Cell technology	Mono-Si
Application class	Class A
Dimension (mm)	1200 x 550 x 35
Weight	8 kg

2-2. Testing procedures

The performance of the photovoltaic module in terms of current, voltage, and power is evaluated for three different types of soiling samples, i.e., soil, ash and sand, as shown in Fig. 2. Moreover, Fig.3, which represents the heavy module covered with soil, ash and sand. The PV module used has an area of 0.55 $m^{2,}$ and the density of soil, ash, and sand is about 1.6 g/mL, 0.007 g/mL, and 1.57g/mL, respectively. The onset of overflowing water from the upper tank is used to cool and cleaning of the photovoltaic module. The water absorbs heat, removes dust particles and collects them in the receiver tank. This receiver tank restores the water again in the storage tank through the pump. This cycle continues to repeat to cool and clean the upper surface of the solar panel, which will be used to evaluate the thermal and optical behavior of the panel.

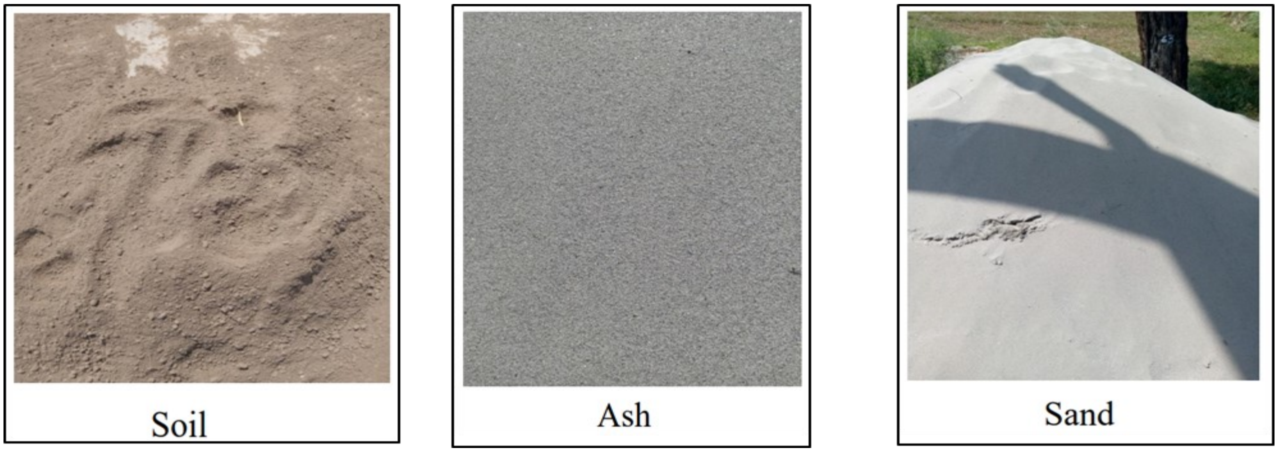

Fig. 2 Three samples of soiling: soil, ash and sand.

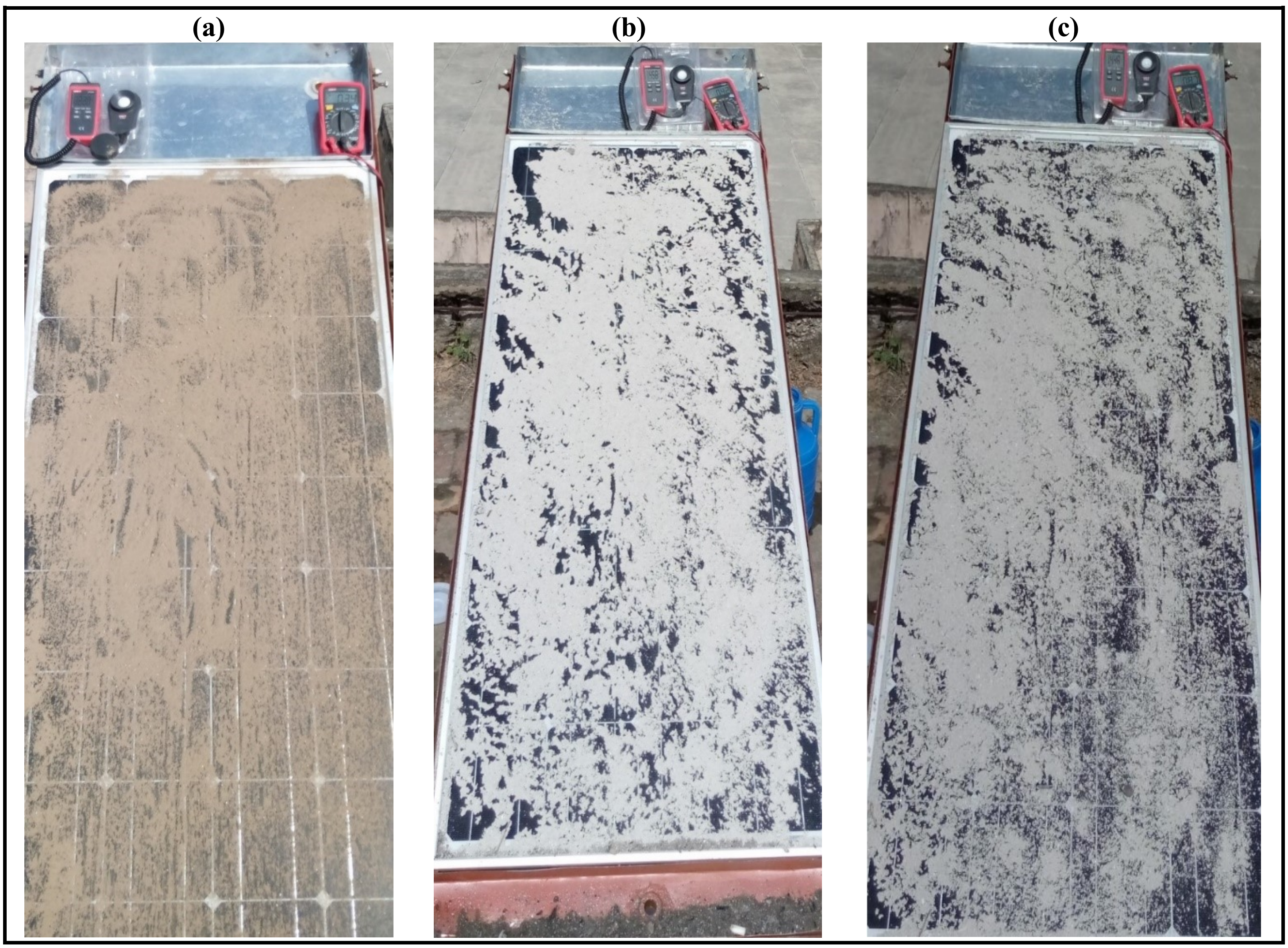

Fig. 3 Solar modules covered with different types of soiling: (a) soil (b) ash (c) sand.

The output power produced from the PV module and the module's efficiency can be quantified using the next equations (1,2), respectively.

$$P = V.I \tag{1}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V.I}{G.A} \tag{2}$$

where (I) is produced current, (P) is the output power, (V) is voltage, (P_{in}) is incident solar radiation, (G) is global solar intensity, and (A) is the area of the PV module. Solar radiation distribution and its intensity are two significant factors that influence the efficacy of solar photovoltaic technology and need to be considered while the design task.

2.3. The surface temperature of the PV module

Exposure of solar PV devices to solar radiation results in some of that radiation being absorbed doesn't converting to electricity; but converted to heat, which causes a rise in the module temperature [36, 37]. However, it is known that water has a refractive index of roughly 1.3, which can improve the optical transmittance of photovoltaic cells/modules when a thin film of water is applied. In addition, flowing the water layer on the top surface of the module decreased sun irradiation reflected by around 2-3.6 % [26, 27]. Therefore, it is also important to consider the environmental temperature when predicting the module temperature. The operating temperature of photovoltaic modules can be quantified by using the following equation:

$$T_{mod} = T_{amb} + \frac{NOCT-25}{800}.G \tag{3}$$

where (T_{mod}) represents the PV module operating temperature, (T_{amb}) is the ambient temperature, and (G) is the global solar irradiance. The (NOCT) represents the nominal operating cell temperature induced on the photovoltaic module.

In the operating condition of the PV plant, the temperature of the solar module is variable on a daily basis; therefore, it depends on the variation of incident solar intensity and environment temperature. Based on that, module variation temperature is given by the relationship (4):

$$\frac{dT_{mod}}{dt} = \frac{dT_{amb}}{dt} + \frac{dG}{dt} \tag{4}$$

where (dT_{amb}), (dG) and (dT_{mod}) are the rates of change of ambient temperature, solar radiation and module temperature, respectively.

2.4. Effect of cooling and cleaning on the module performance

One of the major drawbacks of a photovoltaic module is its low conversion efficiency of solar intensity into electric current. When the solar module is kept in sunlight to generate electric current, its surface temperature also increases because of the sun's intensity. As the solar PV module temperature begins to rise, the voltage starts dropping, and due to this, the efficiency and the power generated from the photovoltaic module decrease significantly. One of the approaches to overcome this issue is cooling the solar PV module to reduce its surface temperature.

In this experiment, the water used, due to its high specific heat value 4200 J/kg.K, will be used to absorb the extra heat of the module. Furthermore, the refractive index of water is 1.3, which improves the optical transmissivity of the solar cells when a thin layer of water is formed on the top surface of the solar module during cooling. The cleaning and cooling method is divided into two categories; full cleaning and cooling. Full cleaning is instantaneous cleaning and stops when the surface is fully clean, while cooling is known as the continuous cooling of surface modules.

Active cooling is one of the effective techniques used for the thermal management of solar PV modules [38]. The cooling heat transfer is given by relationship (5) when the water flows on the top surface of the solar photovoltaic module.

$$Q = Q_{conv} + Q_{rad} \tag{5}$$

where (Q) is cooling heat transfer, (Q_{conv}) is convective heat transfer, and (Q_{rad}) is radiative heat transfer. Hence, the radiative and convective heat transfer from the photovoltaic module by overflowing cooling is given by relationships (6,7) [39, 40].

$$Q_{conv} = h.A(T_s - T_\infty) \tag{6}$$

$$Q_{rad} = \varepsilon.\sigma\,(T_s^4 - T_\infty^4) \tag{7}$$

where (σ) is the Stefan–Boltzmann constant, (ε) is the surface emissivity, (*h*) is the heat transfer coefficient, and (*A*) is the area of the module. (T_s) is the surface temperature and (T_∞) is the environment temperature.

3. Results and discussions

3-1. Effect of soil, ash and sand depositions on the module performance

It is important to be mentioned that one of the challenges of soiling deposition on the PV module surface is causing the hot-spots phenomenon. Thus, it is related to high module temperature and results in a major degradation in performance behavior and integrity of the cell/module [41, 42]. The energy generated by solar modules throughout their effective operating cycle is significantly impacted by soiling deposition, which also affects the financial feasibility of a photovoltaic system [43]. Fig. 4 (a & b) presents the graphical relation between the PV panel performance in terms of current and voltage produced for soil deposition thickness on the module surface. It can observe from the graph that current generation decreases from 2.88 A to 0.34 A when the soil deposition volume increases from 50 mL to 200 mL. Similarly, the PV module voltage drops from 20.4 V to 19.3 V for the soil deposition volume increased from 50 mL to 200 mL.

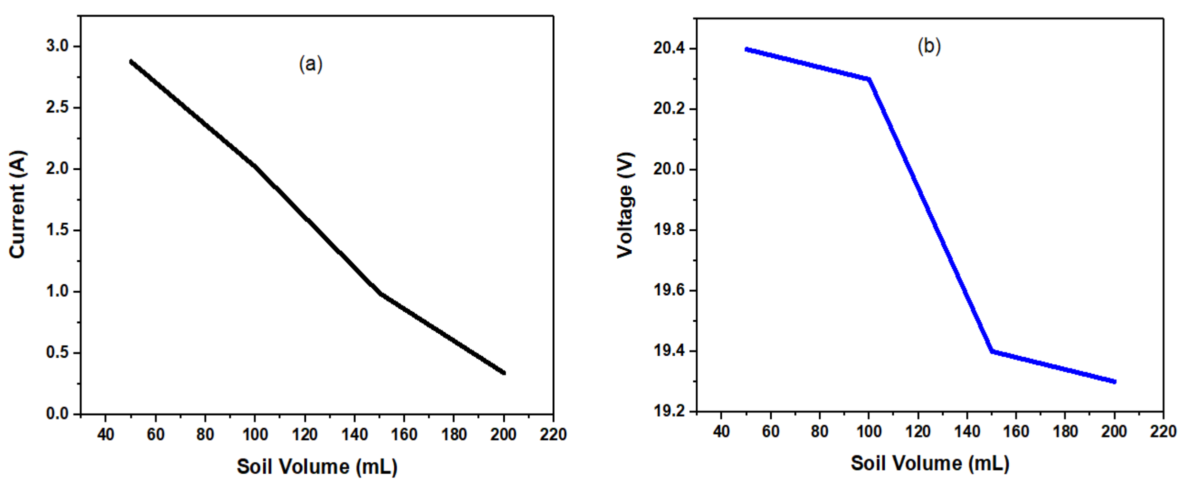

Fig. 4 (a) PV module current and (b) voltage versus soil deposition volume.

The effect of ash concentration on the PV module performance parameters is displayed in Fig. 5 (a & b). As the volume of ash deposition increases from 50 to 200 mL on the module surface, the generated current from the module decreases from 2.17 A to 0.40 A, as shown in Fig. 5 (a). Similarly, Fig. 5 (b) shows the consequence of the rising ash volume from (50-200 mL), that resulting in a voltage drop from 19.9 to 19.2 V.

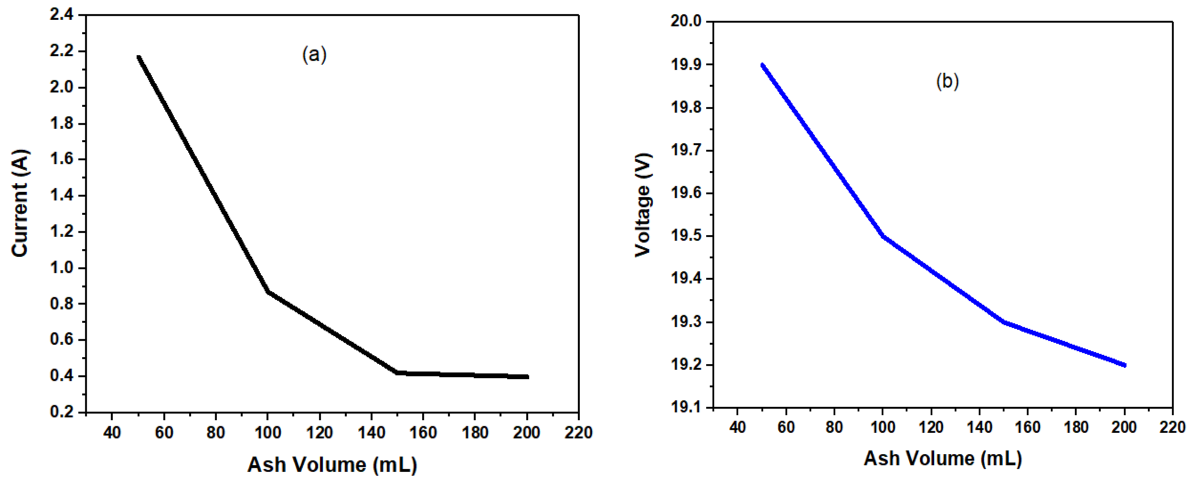

Fig. 5 (a) PV module current and (b) voltage versus ash deposition volume.

The effect of sand deposition on the PV module performance parameters is displayed in Fig. 6 (a & b). At 50 mL volume, the current produced was about 4.09 A, and as the volume increased to 200 mL, the current dropped to almost 2 A, as illustrated in Fig. 6 (a). Also, Fig. 6 (b) shows that with the increase in sand deposition volume from 50 to 300 mL, the voltage is dropped from 20.4 V - 20.1 V.

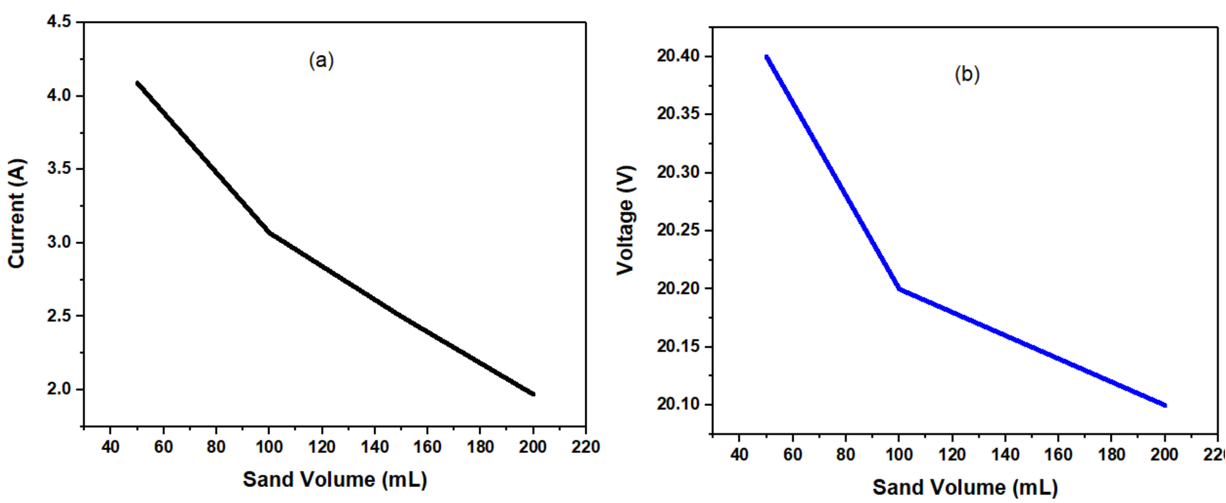

Fig. 6 (a) PV module current and (b) voltage versus sand deposition volume.

Furthermore, Table 3 lists all the types of soiling concentration, incident solar radiation, and corresponding mass of soil. Thus, the volume of soil, ash and sand varied between 50-200 mL; and significantly rose the masses of soil, ash, sand and equivalent solar radiation intensity.

Table 3 Type of soiling versus corresponding concentration, incident solar radiation, and mass.

Type of Soiling	Volume (mL)	Solar radiation (W/m^2)	Mass (kg)
Dry Soil	50	519.7	80
	100	527.9	160
	150	526.2	240
	200	532.7	320
Dry Ash	50	635.2	0.035
	100	628.3	0.070
	150	633.5	0.105
	200	633.9	0.14
Dry sand	50	528.4	78.5
	100	529.6	157
	150	529	-
	200	531.4	314

Fig.7 illustrates the effect of soiling deposition on the solar PV module efficiency at different concentration volumes of ash, sand, and soil. Hence, at 50 mL of sand sample on the module, efficiency was 15.7%; as the volume increased on the module surface to 100, 150, and 200 mL, the module efficiency decreased to 11.7%, 9%, and 7.4%, correspondingly. On the other hand, for the soil volume at 50 mL, the overall efficiency is about 11.3%, which decreases further up to 1.2% as the soil concentration volume increase to 200 mL. Similarly, For the ash volume of 50 mL accumulation on the solar PV module, the efficiency is 6.7%, which also follows the same trend as other soil accumulation and decreases to 1.2% for the volume rises to 200 mL. Thus, it can be concluded that the efficiency varies with the changes in the concentration of sample accumulation on the module surface. It is worth noting that the efficiency standard deviation (SD) was approximately 2.2% for the ash, 3.8% for the soil, and 3% for the sand.

Although in the ash deposition, there is a higher decrease in the module efficiency compared to soil and sand, after that, the soil came in second-level affected the module efficiency. Lastly, the sand has less reduction in efficiency, and that is due to the greater size of the particle. In soiling, the hindrance effect varies with the nature of the dust particles. Whereas dust particles, for instance, it has a greater adhesion force and a stronger undesirable effect than larger dust particles because they occupy smaller spaces and attenuate light, while larger particles leave porous spaces that allow light to pass through [24].

It is clearly shown in Fig. 8 the effect of sand, soil, and ash on the PV module's power at different concentration volumes. For example, at the sand volume of 50 mL, the power is 83.4 W, while for the soil of 50 mL volume, the power is 58 W, and for the ash of 50 mL volume, the power is 43 W. Furthermore, the volume of sand, soil, and ash increased from 50 mL to 200 mL, and the corresponding power decreased to 39 W, 6.6 W and 7 W, respectively.

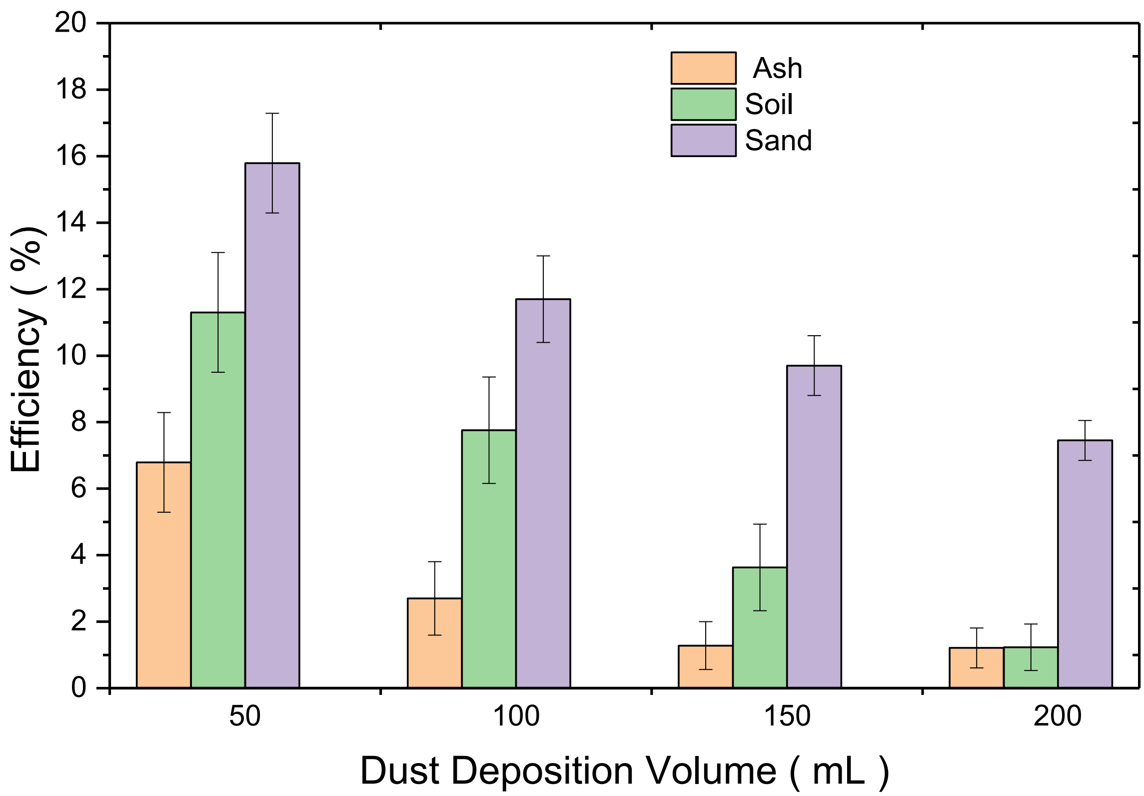

Fig. 7 Effect of soling on the efficiency of the solar PV module.

The variation in the power is due to the change in the amount of debris accumulation on the PV module. The decrease in power was more for small and fine particles like ash deposition and less for large particles. This is because fine particles will not allow the solar light pass due to its small size, while particles like sand have large grain sizes; therefore, light passed to the panel surface from their sides due to coarse size. The effect of sand on the output parameters is less as compared to both soil and ash. This can be because of the greater size of sand particles and having a sliding effect from the surface of the solar cell. It is worth noting that the power's standard deviation (SD) was approximately 15 W for the ash, 14 W for the soil, and 16 W for the sand.

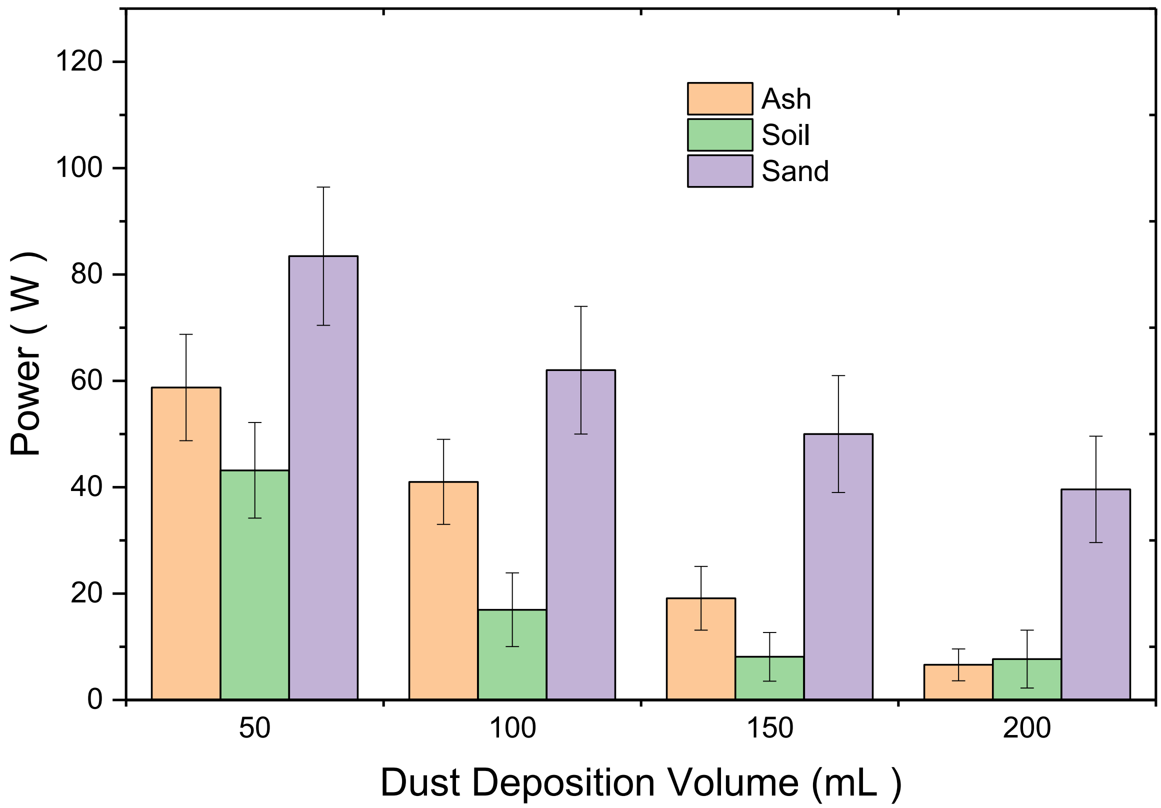

Fig. 8 Effect of dust deposition volume on the power generation of the PV module.

3-2. The surface temperature of the PV module

The operating output of solar cells/modules is influenced significantly by surface temperature. Therefore, in order to keep the surface temperature of the solar module within the best working conditions, we applied the cooling methodology, and the results were greatly encouraging. Freshwater is used to clean and cool the surface, reducing the surface temperature between 10 to 20 ºC within the best working condition of the module, from 30 to 40 ºC.

Also, other considered parameters are the ambient temperature and module temperature at different times of the day before and after cooling the cell, as illustrated in Fig.9. Whereas, the module temperature at normal working conditions (before cooling) was about 60 ºC at 13:45 pm, which drops down to 38 ºC after cooling the cell for 1 minute. Furthermore, the current of the PV panel at normal working conditions is 4.09 A and reaches 5.3 A after cooling the panel.

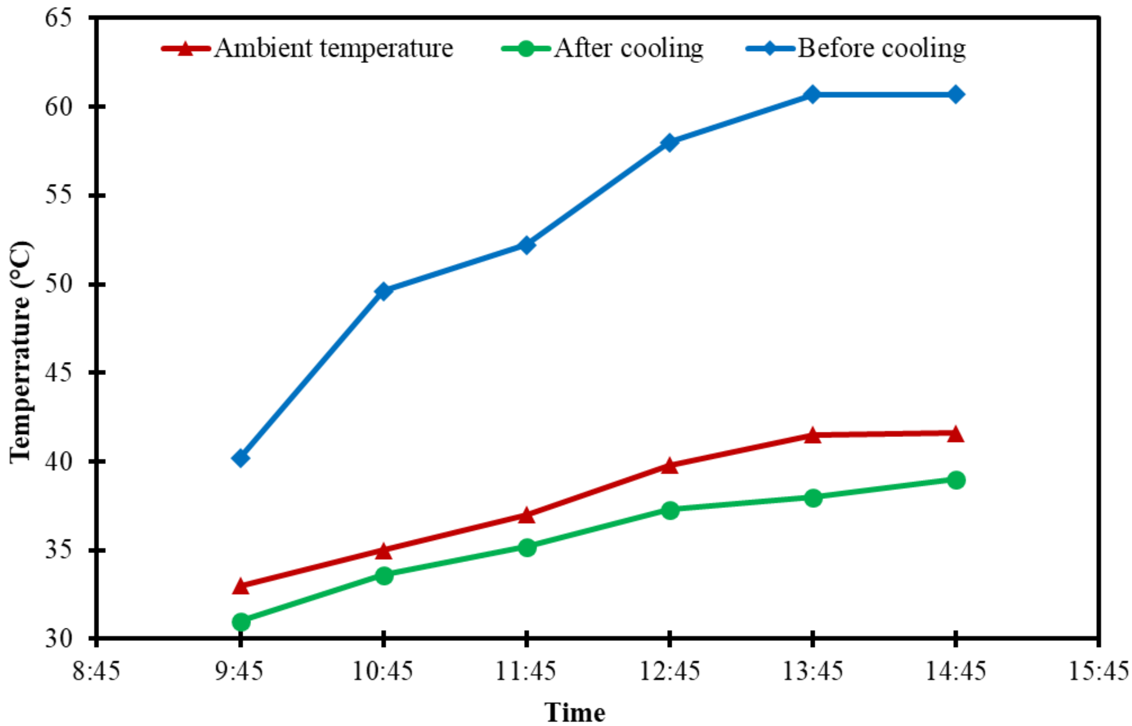

Fig. 9 The ambient temperature and the solar PV module temperature before and after cooling versus time.

3-3. Effect of cleaning and cooling on the module performance

For cooling purposes, the water layer falls on the surface of the plate. This layer of water on the top of the plate plays a dual role. It cools and cleans the module simultaneously to rise the electrical yield via the flowing water over the top surface of the solar photovoltaic module.

It is preferable to keep a low operating temperature as the power output and system efficiency decrease with the rise in operating temperatures. Hence, when comparing the temperature of the traditional solar module, the exploitation of flowing water on the top surface of the photovoltaic module allows the operation at lower temperatures. In addition, the flow of water highly decreases the panel's temperature via absorbing the heat generated during the day.

Fig. 10 illustrates the effect of cleaning and cooling on the PV module performance in terms of power generation and efficiency for different debris. As noted, the full clean can gain the highest efficiency and power improvement compared to a partial clan, drops and almost clean. Furthermore, a full clean can also cool the module and, in turn, will help lower the module temperature and improve its efficacy. Table 4 detailed comparison of full cleaning and cooling versus photovoltaic module performance parameters, e.g., the current, voltage, power, and efficiency. Based on the experiments, the trade-off between cooling and full cleaning depends on the potential. It should also be mentioned that the key consequence of the dirt accumulation influence, it reduces the quantity of sunlight that can reach the solar photovoltaic module's surface.

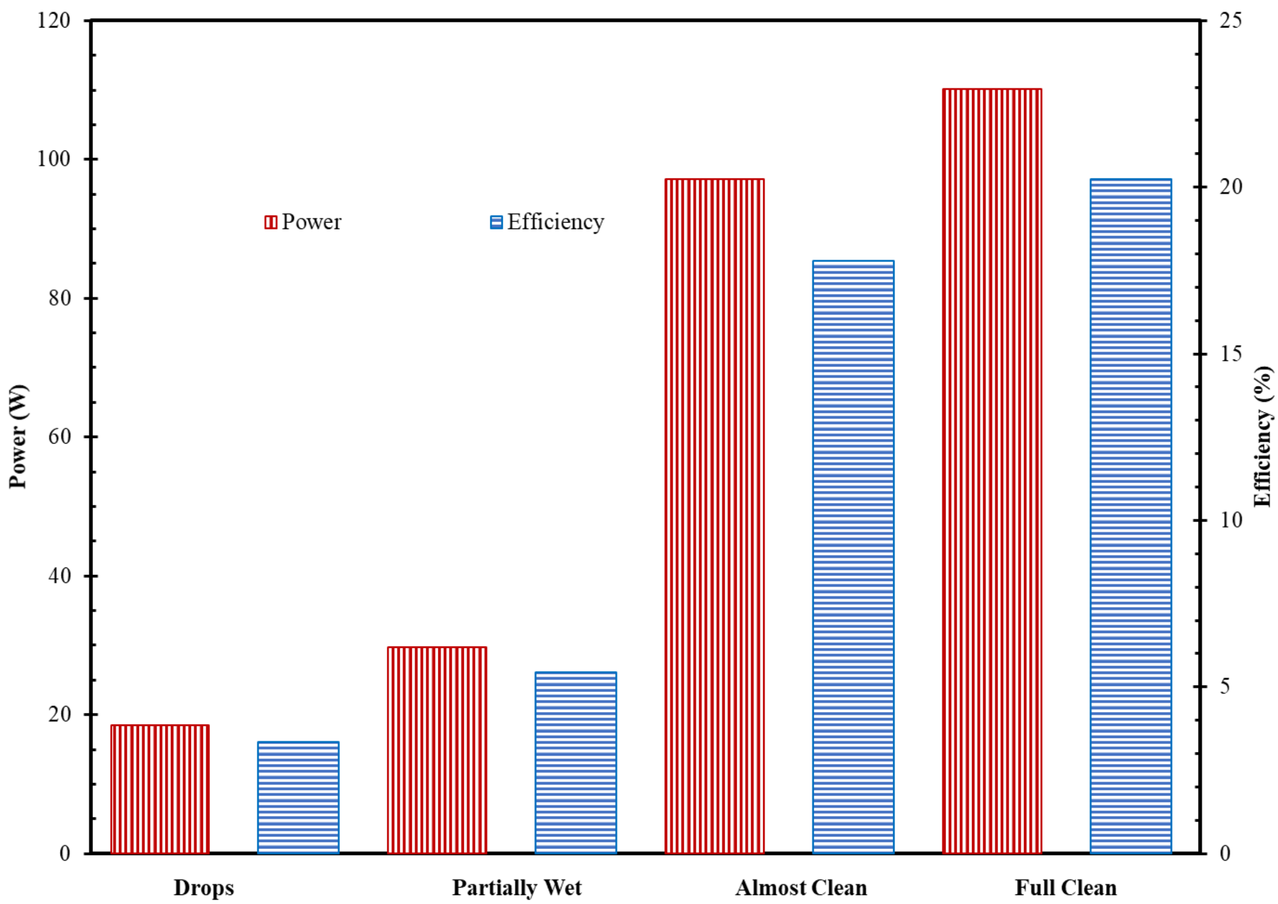

Fig. 10 Photovoltaic module performance versus cleaning and cooling.

Table 4 listed full cleaning and cooling versus solar PV module performance parameters.

	Solar radiation (W/m^2)	Current (A)	Voltage (V)	Power (W)	Efficiency (%)
Full cleaning	544.4	5.35	21.6	110.2	20.24
Cooling	531.8	5.59	20.4	111.9	21.04

4. Conclusions

This work provides the significance of studying a dust disposition and its effect on the performance behavior of the solar photovoltaic modules. The outdoor experimental work is performed on the top surface of the solar photovoltaic modules. This investigates the effect of the deposition of three different samples of soiling (soil, sand and ash) on solar PV module performance behavior. In addition, water flows on the plate surface are also considered in this manuscript to study the effect of cleaning and cooling on the solar panel performance parameters in terms of current, voltage, power, and efficiency. But, when the water flows on the plate surface to clean and cool, almost 3-4% efficiency of the PV module increases.

Based on the outcomes, it can be concluded that the ash has a major effect on the performance behavior of the solar PV module, and even a 50 mL of ash covering the plate surface reduces almost 50-60% of the current production capacity of the solar plate and thus affect the performance badly. Comparatively, the sand has the lowest effect on the performance behavior of solar photovoltaic modules. The sand layer of volume 50 mL reduces only about 20-25% of the current production capacity; hence, it has less effect on the performance. Furthermore, it is also observed during the experimental work that wet accumulation of dust particles promotes retention of more dust particles on the surface module because the capillary forces act as the bridge between the plate and the dust particles. Further suggested works include an experimental study of seasonal, annual and decade environment variation effects on the module performance. Also, a techno-economies feasibility study of soiling losses is highly required to assess solar PV applications.

Nomenclature

A	Area of the module (m^2)
I	current (A)
h	heat transfer coefficient
G	global solar radiation (W/m^2)
R_s	resistance (ohm)
P_{out}	output power (W)

P_{in}	incident Power (W)
P_{max}	maximum power (W)
P	power (W)
V	voltage (V)
T_{amb}	ambient temperature (ºC)
T_{mod}	module temperature (ºC)
Q	cooling heat transfer
Q_{conv}	convective heat transfer
Q_{rad}	radiative heat transfer

Greek letters

ε	surface emissivity
σ	Stefan–Boltzmann constant
η	efficiency

Abbreviations

RE	Renewable Energy
STC	Standard Test Condition
PV	Photovoltaic
NOCT	Nominal Operating Cell Temperature
SD	Standard Deviation

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