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Experimental analysis on the impacts of soil deposition and bird droppings on the thermal performance of photovoltaic panels

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ABSTRACT

Photovoltaic (PV) systems are capable of meeting the urgent demand for power production for both domestic and commercial purposes. PV systems possess serious drawbacks as their performance is heavily influenced by environmental variables like wind, radiation, shadow, dust, and soil accumulation. The current work examines the performance of solar PV panels in the presence of soil and dust at various tilt angles. A solar PV simulator was used, and experiments were conducted for a hot-dry climate location (Vellore, Tamil Nadu, India, 12.91° N, 79.1325° E), to evaluate the performance of solar PV panels under varying dust deposition. A total of seven different samples, such as black soil, desert soil, red soil, alluvial soil, laterite soil, coal dust, and bird droppings, were selected and dispersed over the surface of the PV panel at various weights of 10, 20, 30, 40, and 50 g. The physical characteristics of the dust samples have been emphasized as being essential in determining how effectively the PV panel functioned. Bird droppings were shown to have the greatest influence on PV panel efficiency because of their tendency to stick to the panel surface due to moisture content, but coal dust, independent of tilt angle, was found to have the least effect. Coal dust was determined to have the least impact of all soil types since it is quickly blown away and does not stick to the surface. Bird droppings accounted for about 46.42 %–89.18% of the efficiency loss, which was determined to be high, whereas coal dust accounted

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for less than 13% of the efficiency loss. Furthermore, it was revealed that considered tilt angles (0^O and 12.91^O) have a minor influence on the PV's overall performance.

Nomenclature

I_{MP}	Current at maximum power
I_{SC}	Short circuit current
P_{max}	Maximum power
V_{MP}	Voltage at maximum power
V_{OC}	Open circuit voltage
η	Efficiency
η_{loss}	Efficiency loss

Acronyms

EMF	Electromagnetic field
PV	Photovoltaic
FF	Fill Factor

1. Introduction

Solar energy has a lot of promise for power generation and integration into building design as a readily accessible energy source that is also completely clean. They are therefore viewed as an alternative to depleting fossil fuels, which cause greater emissions and pollute the environment [1]. PV panels can convert solar energy directly into electricity, but it is essential to note that the ideal tilt angle varies depending on the environment of the site. In parallel, the efficiency of PV panels is heavily influenced by several parameters, including the climate, latitude, and time of operation, as well as atmospheric variables like dust and soiling [2]. Electricity generated by using PV panels has increased rapidly in recent years, and by the end of 2021, it had reached 942 million kilowatts, up almost 23% from the previous year [3].

The regions with an arid desert climate, high temperatures, large records for sun radiation, and the presence of dust and sand, are where solar PV panels are most suited for installation [4,5]. However, when dust accumulates on them, it will act as a shield, potentially preventing solar energy absorption. In addition, since the PVs are used outdoors for a prolonged period of time, some particle sources, such as soil, atmospheric pollutants, and bird droppings, accumulate on the surface of the panel. It is important to note that this reduces the efficiency of using solar energy sources in areas where there are higher levels of solar radiation and dust accumulation [6]. Initially, it was suggested that the tilt angle be the same as that of the altitude of the location, which was further conveyed as latitude +15° as the optimal tilt angle [7,8]. The accumulation of soil and dust particles on the outer surface of PV panels generates a very thin layer that is less than 500 m thick, regardless of the environmental regime (climate) or the location. This layer, in particular, is highly dependent on gravity settling (sedimentation) and acting forces brought on by the wind [9].

According to an experimental investigation by Ahmed Amine Hachicha et al. [10], it was discovered that particles smaller than 25 m were responsible for a 12.7% reduction in efficiency over the course of more than 5 months in Sharjah, UAE. Nabil Ammari et al. stated in [11] that Poly-Si is significantly more affected by soiling than CdTe with reductions in energy production of 15% and 13%, respectively, in Morocco under a hot arid climate. From a different angle, Naveed Hussain et al. [12] studied soiling in a controlled environment by varying parameters of tilt angle, humidity, temperature, and wind speed and reported that at a tilt angle of 60°, the soling loss was less at 13.70%, compared with the maximum soling loss of 25.71% at a tilt angle of 0°. Furthermore, Abdelouahed Chbihi et al. [13] conducted a case study in which they compared three PV devices in two different Moroccan cities and discovered a considerable power loss of 29% after one month of exposure to the environment. In [14], Rizwan Majeed et al. carried out an experimental investigation for dust accumulation studies utilizing monocrystalline (mono-PV) and polycrystalline (poly-PV) PV modules, and they revealed that with 4.6 g/m^2 dust density, the output power was reduced by 16% and 11% in mono-PV and poly-PV installations, respectively. The fact that dust can accumulate on solar panels as either wet or dry deposition was also emphasized in the aforementioned study. Wet deposition refers to dust particles that adhere to water molecules under humid conditions, while dry deposition refers to dust particles generated by air movement during dry conditions.

Parallel to this, it was demonstrated in [15] that several parameters, including temperature, humidity, rainfall, etc., affect the deposition of dust, with wind being the most important one. Therefore, it was found that the wind boosted diffusion and accelerated deposition, while on the other hand, it was shown that an increase in wind speed prevented dust accumulation on PV panels. In addition to dust accumulation, other factors such as pollution, bird droppings, agricultural and engine emissions, algae and fungi may also contribute to soil deposition on solar panels [16]. Soiling not only reduces the quantity of energy produced by solar-powered systems like PV, CPV, etc., but also increases annual running-operating and maintenance costs to a certain extent [17]. Similar to the previous studies, Basant Raj Paudyal et al. [18] completed an outdoor study to examine soiling in outdoor conditions with two modules, one of which was cleaned daily and the other left uncleaned; when compared to the well-preserved module, they found that the efficiency of the soiled module was 29.76% lower.

Hao Lu and Wenjun Zhao [19] reported on a numerical method using the k-ω turbulence model to analyze the dust deposition behaviors using an isolated ground-mounted solar PV system. They reached the conclusion that the dust deposition rate is higher for ground installed PV systems when compared to rooftop installed systems, and that more dust is also accumulating at a fixed tilt angle when compared to single or double axis tracker based solar PV modules. Moreover, Zeki Ahmed Darwish et al. [20] evaluated an indoor PV module by taking into account a continuous solar radiation source of 600 W/m^2. It was revealed that dust contained carbon (C), iron oxide, manganese dioxide, calcium oxide, and natural dust particles, with carbon and natural dust showing the highest (95.90%) and lowest (90.52%) reductions in load, respectively.

Outdoor experimental studies are a complex and are affected by many external factors on the PV panel's performance, for which an indoor system can be designed where the influencing parameters can be controlled with respect to optimum levels and outdoor devices will take longer period to attain a stable condition which can be attained in a shorter time using indoor systems [21].

In an effort to fill the knowledge gap, this work examines the performance of solar PV panels under various tilt angles when exposed to different kinds of soil and dust. The current study primarily focuses on the power variations, efficiency of PV panels, and corresponding loss in efficiency for different soil depositions under indoor conditions. In that aspect, the sample types that were explicitly examined on solar PV panels were black soil, desert soil, red soil, alluvial soil, laterite soil, coal dust, and bird droppings. These samples were spread out on the surface of PV panels at varying weights of 10, 20, 30, 40, and 50 g. With the use of a solar PV simulator, it was possible to determine the efficiency of PV panels under two various tilt angles and soil deposition. On this premise, emphasis has been placed on the estimation of power variation, maximum power, fill factor, panel efficiency, and efficiency loss.

2. Materials and preparation

This study aims to experimentally investigate the performance of photovoltaic modules and the efficiency loss brought on by various soil types, and bird droppings common in Indian landforms.

2.1. Outline of the PV panel system

A standard Solar Photovoltaic Simulator was used to ascertain the effects of various soils, and bird droppings on the energy efficiency solar photovoltaic panels. The schematic depiction of the photovoltaic module circuit diagram and the I–V curve measurement are shown in Fig. 1. In addition, Table 1 provides a summary of the technical specifications for the PV simulator.

The strategies used for the research efforts were undoubtedly similar to those according to the literature reviews. The current study was carried out using solar photovoltaic simulators that are considered to comply with the industry standards. Nevertheless, there are certain differences, such as the fact that each research study accepts a different amount of solar energy based on pyranometer measurements.

In this research work, a standard solar photovoltaic simulator developed by Ecosence available at the Renewable Energy Systems Laboratory, Vellore Institute of Technology, Vellore, Tamil Nadu, India was utilised. The experimental setup of the solar PV simulator is shown in Fig. 2. The solar PV simulator consists of halogen lights (with regulator) of total 1800 W (for both PV panels), which produces artificial radiation. It has two polycrystalline PV modules of 40 W power rating each. The distance between artificial radiation source and PV panel is 65 cm. The dimension of each PV panel is 65 × 45 cm.

In the study, Retsch sieve shaker was employed to distribute the samples evenly across the panel. This shaker collects particles of the same size at first and distributes them uniformly throughout the panel. The sieving procedure is repeated to reduce estimation error.

2.2. Main characteristics of examined soil samples

The materials used in this investigation were soil samples that were gathered from various sites throughout India. Within this framework, there were a total of seven samples used for the research study, including alluvial soil, red roil, laterite soil, black soil, grey soil, desert soil, and bird droppings. Fig. 3a displays the samples used in the current study, while Table 2 provides a list of the main features of the analysed samples.

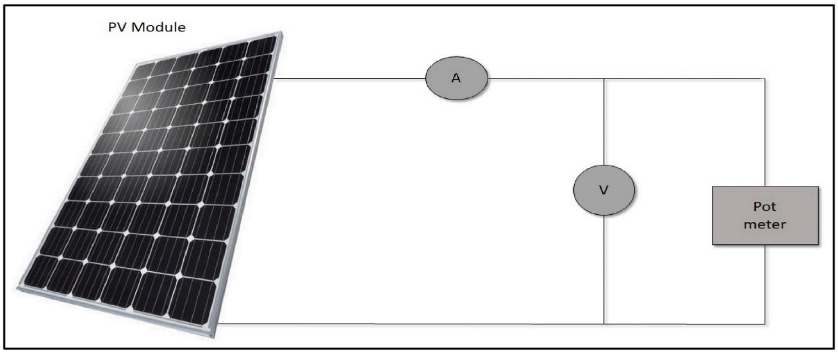


Fig. 1. Photovoltaic module circuit diagram, with respect to the I–V Curve measurement procedure.

Table 1
Technical Specifications of photovoltaic Simulator.

S.No.	Instrument	Manufacturer	Components	Accuracy	Sensitivity
1.	Solar PV simulator	Ecosense	-Polycrystalline panels: 02 -Power rating/panel: 40 W -Artificial light source power/panel: 900W	±5%	–
2.	Pyranometer	Hukseflux Thermal Sensors	-Hemispherical solar radiation measurement -Rated operating temperature range: -40 to +80 °C -Temperature response: <±2%	±10%	15×10^{-6} V/(W/m^2)

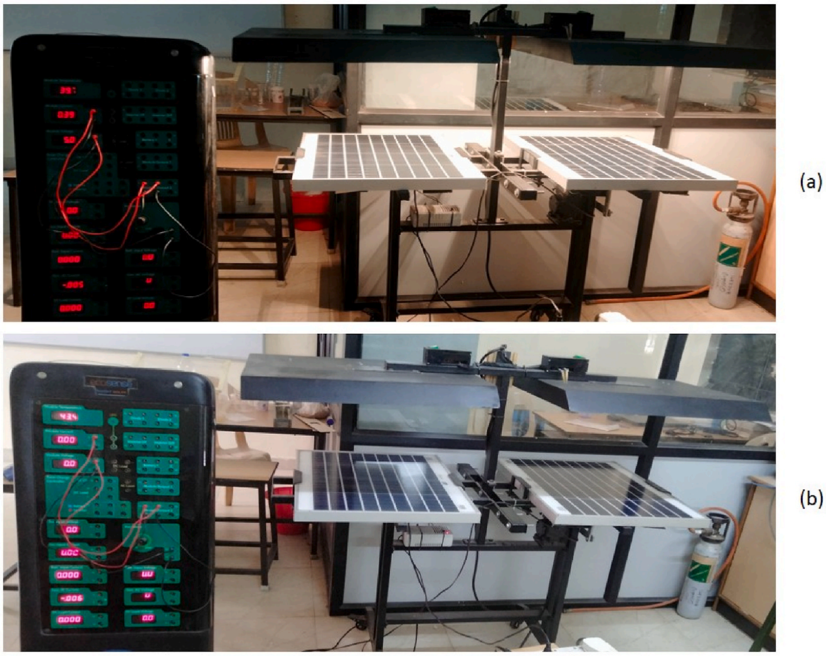


Fig. 2. Photovoltaic module experimental setup.

(i) **Black Soil:** Black soil is also referred locally as cotton soil and globally as "Tropical Chernozems". Cretaceous lava rocks are the primary constituents of this soil. Black soil is created by weathering of lava rocks and has high iron, alumina, and magnesia concentrations and is black in complexion. Black soil is sticky when it is wet and splits when it is dry because it is rich in calcium, carbonate, and potash and can retain moisture. The volcanic explosion creates black soil, which is very productive and ideal for intensive cultivation.

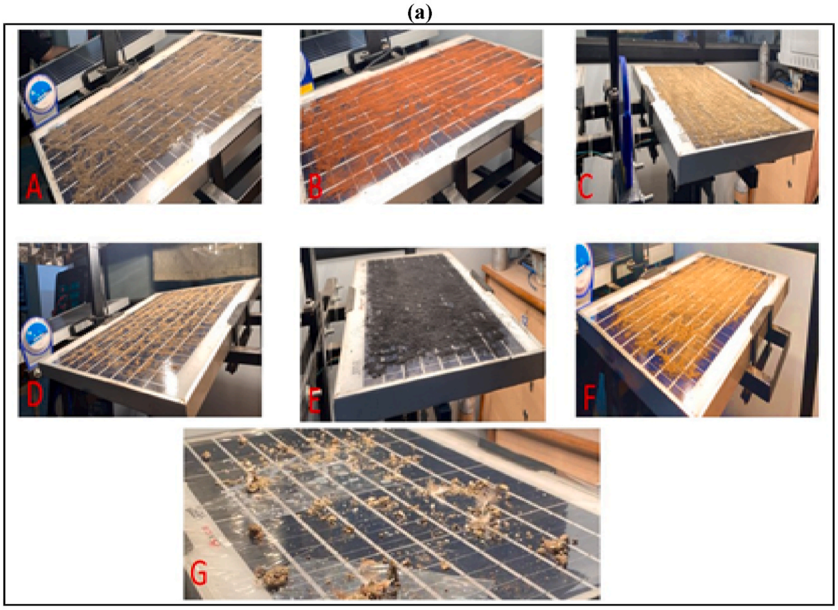
(ii) **Desert Soil:** Desert soil (90–95% sand) is found in areas with little or no rainfall. It is infertile because of its high calcium carbonate and phosphate concentration and low nitrogen level. The calcium content of the subsoil is ten times greater than that of the topsoil. This soil is vulnerable to wind erosion and can only sustain a small population. Deserts lack any significant source of water, therefore the natural process of chemical weathering is greatly reduced or eliminated entirely.

(iii) **Coal Dust:** The process of crushing, grinding, or pulverizing coal results in the production of a finely powdered version of the substance known as "coal dust". Due to the brittle behaviour of coal, coal dust may be generated during the mining process, when coal is being transported, or while coal is being mechanically handled. It may be categorized as a kind of fugitive dust. Meshes are typically used as the unit of measurement for determining the size distribution of the particles that make up coal dust. Acutely, it may cause an explosive combination in the air, and long-term, it can cause lung disease in those who inhale large amounts of it.

(iv) **Red Soil:** There is a kind of soil known as red soil, and it often forms in temperatures that are warm, moderate, and humid. Red soil accounts for around 13% of all of the earth's surface. It is composed of thin coatings of organic and organic-mineral soil that have been heavily leached, and it is over a layer of alluvium that is red in colour. The weathering of old crystalline and metamorphic rocks often results in the formation of red soils, which are typically rich in clay and contain significant concentrations of this mineral.

(v) **Laterite Soil:** Laterite is a kind of soil and rock that is abundant in iron and aluminium. It is generally thought to have originated in regions of the tropics that were formerly hot and humid. Due to the presence of large levels of iron oxide, almost all laterites are described as rusty. The term "tropical weathering" refers to a lengthy process of chemical weathering known as

(a)



(b)

Fig. 3. (a) Examined soil samples used in the current study, (b)Various soils and birds drop on the studied solar panels: (A) Black soil; (B) Red soil; (C) Alluvial soil; (D) Desert soil; (E) Coal dust; (F) Laterite soil; (G) Bird drops. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Physical properties of collected soils.

Property	Black Soil	Desert Soil	Red Soil	Alluvial Soil	Laterite Soil	Coal Dust
Specific Gravity	2.51-2.70	2.66	2.69	2.60	2.67	2.15
Liquid Limit (%)	68.00	20.00	41.00	40.60	76.00	47.00
Plastic Limit (%)	27.00	0	19.00	30.30	42.00	0
Shrinkage Limit (%)	11.00	0.008 to 1	6.00	13.00	18.65	20.00
Maximum Dry Density (kN/m^3)	15.50	16.70	16.20	2.66	1.84	1.059
Minimum Dry Density (kN/m^3)	14.74	12.30	9.60	2.52	1.78	0.89
Optimum Moisture Content (%)	25.21	35.00	26.20	19.65	13.00	35.00

"laterization". This process generates a broad range of variations in the thickness, quality, chemistry, and ore mineralogy of the soils that are produced as a consequence.

(vi) **Alluvial Soil:** Surface water accumulates in soils known as alluvial soils. For young alluvial soils, the features of the alluvial parent material play an important role in shaping the soil's morphology, physical, chemical, and mineralogical qualities. Soil characteristics are influenced by different elements as alluvial soils grow through time.

The samples that were collected were sieved, and to obtain the standard size of the particles, the shiver was employed with corresponding sieve holes. After the samples were collected, each one was weighed in a digital scale before being distributed in weights ranging from 10 g to 50 g on the PV panel.

2.3. Framework of the experimental setup

In the experimental set-up, a pyranometer and digital multimeters were used to detect the radiation intensity. It should be mentioned that the term “pyranometer instrument” refers to a device used to gauge diffuse or global radiation reaching a horizontal surface over a hemispherical region. A pyranometer is characterized by a “black surface” that generates heat when subjected to a solar radiation excitation. Its temperature will endure to upsurge until the rate of heat gained from the inbound sunlight is identical to the rate of heat removed by convection, conduction, and radiation. The thermopile’s hot junctions are coupled to the black surface, while the cold connections are sheltered from radiation by placing behind a protective plate. Therefore, the aforementioned regime results in the generation of an electromagnetic field (EMF). EMFs in the range of 0 mV–10 mV are often used to assess global radiation and may be read, recorded, or integrated over a period of time. In the context of this work, the Ecosence Solar PV Simulator was used to monitor and record current and voltage values.

After the samples had been prepared to the required size, a shudder was used to evenly distribute them throughout the panel. The samples were dispersed over the panels in weights of 10g, 20g, 30g, 40g, and 50g. The experiments were conducted at an ambient temperature ranging from 37.2 °C to 38.4 °C and at two different tilt angles of the solar panels; in that respect, a horizontal surface of 0° and a surface having a tilt angle of 12.91°, identical to Vellore latitude, were thoroughly studied. Pyranometer measurements of the sun irradiation in Vellore were made at a horizontal surface angle of 0° and a tilt angle of 12.91°. The pyranometer readings are illustrated in Table 3. After obtaining these results from the pyranometer, experiments were initiated to study about the performance of the panel in the presence of various types of soil. In that respect, Fig. 3b shows the different soil types and bird droppings that have been observed on the investigated PV panels.

3. Experimental and analytical methodology

Readings were obtained for each soil sample and weight under conditions of constant radiation intensity, which was determined using a pyranometer. The simulator aided in upholding a stable intensity. The mean of five pyranometer readings observed in the centre and at each of the four corners were used to compute the radiation intensity. To attain the utmost degree of homogeneousness, the samples were first dispersed using a shiver and then physically spread by brush. The same methodology was adopted for the solar panel tilt angles at the horizontal surface of 0° and the Vellore latitude of 12.91°.

For each sample and tilt angle, short circuit current (I_{SC}), open circuit voltage (V_{OC}), current at maximum power (I_{MP}), and voltage at maximum power (V_{MP}) were measured and maximum power (P_{max}) and fill factor (FF) were obtained using Eqs. (1) and (2). On this basis it is possible to determine and generate charts referring to the efficiency (η) and the efficiency loss (η_{loss}). Evidently, it has been demonstrated that soiled solar panels perform less effectively.

$$P_{max} = I_{MP} \times V_{MP} \tag{1}$$

$$FF = \frac{V_{MP} * I_{MP}}{V_{OC} * I_{SC}} \tag{2}$$

Accordingly, the efficiency η of a PV panel can be derived by:

$$\eta = \frac{P_{max}}{Radiation\ Internsity \times Area\ of\ Panel} \tag{3}$$

Moreover, the efficiency loss η_{loss} (decrease in efficiency) of a PV panel is given by:

$$loss\ in\ \eta = \frac{(Efficiency\ of\ Reference) - (Efficiency\ of\ Panel\ for\ the\ Sample)}{Efficiency\ of\ Reference} \tag{4}$$

It should be emphasized that the efficiency of the reference case refers to the panel’s efficiency prior to soiling, or in other words, the panel’s efficiency while it is clean. In addition, we have calculated the maximum power (P_{max}) by multiplying each output reading, such as current and voltage, and taking the highest number. The minimum circuit current (also known as short current) is the flow of current through the PV circuit when the voltage is at its lowest. On the other hand, when the voltage is at its highest, the maximum circuit current (also known as long current) is the amount of current that flows through the PV circuit.

4. Results and discussion

The quantity and type of dispersed particles are the crucial elements that influence how well solar panels perform. Smaller particles tend to have a high surface to volume ratio, which prevents more light from entering and lowers the efficiency of the panels. On the contrary, dispersion of large-sized particles causes the finer particles to settle down as a denser coating on the surface of the panel. Furthermore, it takes less energy to clean larger size particles [22].

Table 3
Pyranometer readings at different tilt angles.

Tilt Angles of Photovoltaic Panel	Pyranometer Reading
Pyranometer reading at the horizontal surface of 0° tilt	375.65 W/m^2
Pyranometer reading at Vellore latitude of 12.91° tilt	366.50 W/m^2

4.1. *Power variations of PV panels for various tilt angles and soil deposition types*

The variation in power produced by changing the tilt angle and altering the amount of soil scattered on the photovoltaic panel was studied by using a solar simulator in an indoor system. and the results are discussed in the following sections.

Initially, Fig. 4a depicts the variation of power of the studied PV panels by varying the amount of soil deposition with a tilt angle at a horizontal surface of 0°. In all of the samples, the power was observed to decrease with an increase in the scattered particles on the panel, which is mainly attributed to the samples present on the PV panels absorbing most of the solar energy incident on them, leading to a decrease in power produced. Bird droppings were found to cause a maximum power reduction due to the presence of moisture content in the sample. This reduction was demonstrated to be 3.43 W–0.63 W in the presence of 10 and 50 g of deposition, respectively. Coal dust was shown to have the slightest power drop from 4.75 W to 4.30 W in the presence of 10 and 50 g, respectively, which is mainly due to the samples getting washed away in the presence of wind and they will not form any thicker deposition on the panel. All the samples followed the same trend in the reduction of power with increase in the sample content on the panel.

Moreover, Fig. 4b shows the power variation of the analysed PV panels as a function of the amount of deposited soil, with a tilt angle of 12.91°at Vellore latitude. Similar to the power variation at a tilt angle of 0°, the same trend was observed with a tilt angle of 12.91°. Bird drops were found to induce a power drop that ranged from 2.29 W to 0.36 W in the presence of 10 g and 50 g, respectively. In an analogous way, coal dust was shown to produce the lowest power drop from 3.26 W to 3.34 W in the presence of 10 g and 50 g, respectively. We can see the same pattern that was seen with a tilt angle of 0°, and it is primarily caused by bird droppings' high initial moisture content and strong long-term sticking nature, which result in low power production, in contrast to the high particle size of desert soil, which results in less of an impact. Overall, it was shown that power variations were lower for coal dust due to the finer particles and higher for bird drops due to moisture content. Both of the tilt angles under examination exhibit this trend.

4.2. *Efficiency of PV panels for various tilt angles and soil deposition types*

Generally, the efficiency of the photovoltaic panel will decrease with a rise in soiling and dust content. This trend was noticed in the current work irrespective of the amount of sample (ranging from 0 g to 50 g, in steps of 10 g) and for both assumed tilt angles.

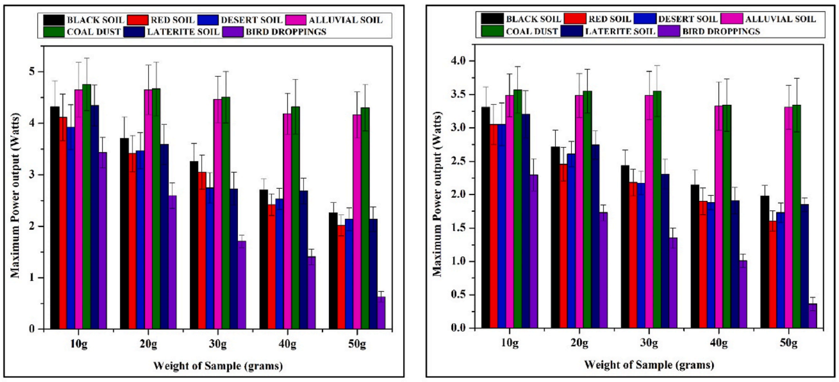
Fig. 5a illustrates the efficiency variations of the PV panels with respect to a tilt angle at a horizontal surface of 0°. Bird droppings were shown to have a significant impact on efficiency, dropping it from 2.9% to 0.5% in the presence of 10 and 50 g, respectively. This is mostly because the bird droppings cling to the panel, obstructing light and radiation from reaching the module and causing a reduction in efficiency. Corresponding findings for coal dust were found to exhibit a lower efficiency change of 4.1% and 3.7% in the presence of 10 and 50 g, respectively which is mainly due to the coal dust getting flied away in the presence of wind thereby having lesser impact on the efficiency of the PV panel. Alluvial soil was shown to underline an almost identical efficiency of 4.0% and 3.6% in the presence of 10 and 50 g, respectively. On the other hand, black, red, desert and laterite soils were found to have a much lower efficiency; accordingly, the corresponding efficiency was shown to be approximately the same (1.9%, 1.8%, 1.8% and 1.8%, respectively) in the presence of 50 g of the sample.

Fig. 5b indicates the variations in efficiency of the PV panels with regard to a tilt angle at Vellore latitude of 12.91°. Since the observed results in this instance were nearly comparable to the horizontal case scenario (tilt angle of 0°), a similar pattern to that previously found was made evident. Therefore, the margins of efficiency reduction in the presence of 10 and 50 g of a particular sample were 1.9%–0.3%, 3.2%–3.1%, and 3.1%–2.7%, respectively, for bird droppings, coal dust, and alluvial soil. Finally, in the presence of 50 g of the sample, the black, red, desert, and laterite soils revealed a nearly comparable efficiency of 1.4%.

4.3. *Efficiency loss of PV panels for various tilt angles and soil deposition types*

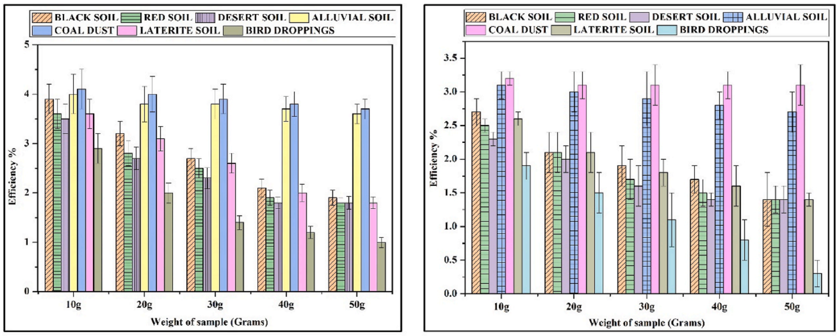
PV panel efficiency loss is primarily influenced by output power and solar irradiation; however, these variables can change due to the effects of dust and soiling.

Fig. 6a shows the loss in efficiency of the examined PV panels with a tilt angle of 0° referring to a horizontal surface. Coal dust was



(a) (b)

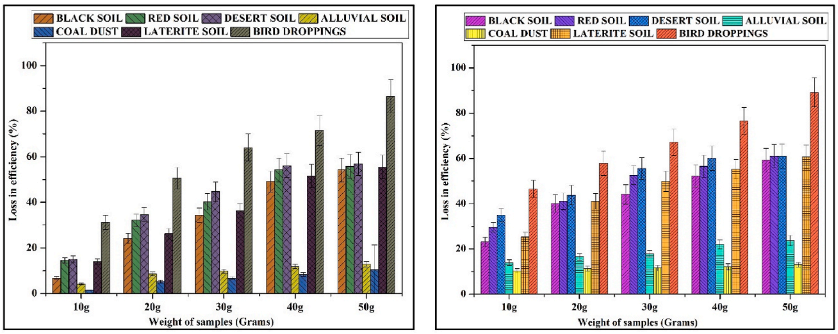
Fig. 4. (a) Power variations with a tilt angle of 0° (horizontal surface), (b)Power variations with a tilt angle of 12.91° (Vellore latitude).



(a)

(b)

Fig. 5. (a) Efficiency of PV panels with a tilt angle of 0° (horizontal surface), (b) Efficiency of PV panels with a tilt angle of 12.91° (Vellore latitude).

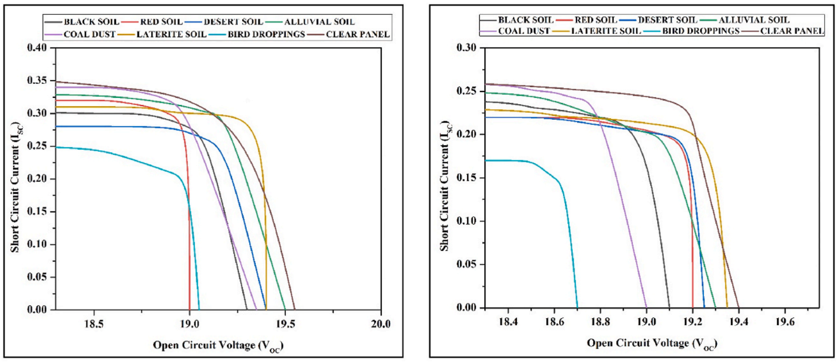


(a)

(b)

Fig. 6. (a) Loss in efficiency of PV panels with a tilt angle of 0° (horizontal surface), (b) Loss in efficiency of PV panels with a tilt angle of 12.91° (Vellore latitude).

seen to have the least efficiency loss from 1.45% to 10.47% with the presence of 10 g and 50 g, respectively. This decrease in efficiency for this case might be caused by the particles being swept off the panel by the wind, and in some situations, coal dust has a propensity to precipitate and form a coating on the panel. Furthermore, it was discovered that 50 g of the sample caused an efficiency loss of 54.2%, 55.74%, 57%, and 55.49% in black, red, desert, and alluvial soils, respectively. The highest efficiency loss was observed for bird drops, which ranged from 31.25% to 86.53% in the presence of 10 g and 50 g, respectively. Bird droppings typically hold moisture for a long time, which tends to cool the panel's top surface, block light and heat from entering the module, and decrease efficiency. Fig. 6b illustrates the reduction in efficiency of PV panels at a tilt angle of 12.91° in Vellore. The change in tilt angle was accompanied by the same pattern of efficiency loss. Coal dust caused the least efficiency loss, ranging from 10.27% to 13.01%, in the presence of 10 g and 50 g, respectively. On the other hand, it was determined that the maximum efficiency loss for bird drops ranged from 46.42% to 89.18% when there were 10 g and 50 g present, respectively. It was found that the efficiency loss of black, red, desert, and alluvial soils was 59.26%, 61.08%, 60.99%, and 23.67%, respectively, in the presence of 50 g of the sample. Moreover, the efficiency loss of laterite



(a)

(b)

Fig. 7. I-V Curves of the panels (a) with a tilt angle of 0° (horizontal surface), (b) with a tilt angle of 12.91° (Vellore latitude).

soil was determined to be 55.49% and 60.64% at tilt angles of 0° and 12.91°, respectively. Therefore, the soil on the panel will tend to slip off due to gravity as the tilt angle increases, leaving less soil on the panel and having less of an impact on the performance of the PV panels.

4.4. I–V characteristics at varied tilt angles

The I–V curves of the studied PV panel in the presence of various dusts and the bird droppings with respect to varied tilt angle are depicted in Fig. 7 and the corresponding I–V characteristic values are listed in Table 4. I–V curves are used to study about the change in current and voltage in the presence of various soils and bird dropping on the PV panel. Generally, the I–V curves are used to characterize the performance of the panel and also to diagnose the degradation of power produced by the panel. I–V curve is used to study about the maximum power peak for maximum power generation. Fig. 7 a depicts the I–V curve at tilt angle of 0°. Coal dust was found to have the least impact on power generation which is mainly due to the particles not getting sticked with the panel and bird droppings have been found to have the greatest effect on energy generation, which is mostly because of the moisture content contained in the sample, which clings to the panel aggressively. The transfer of heat and light to the panel is greatly impeded by these sticked bird droppings [23,24]. Fig. 7 b depicts the I–V curve at tilt angle of 12.91° where the same trend as that of tilt angle 0° was observed. In both the observed tilt angles, the I–V curve was found to have a concave shape. For all of the investigated soil dusts and bird droppings, the variation in fill factor was found to be between 70 and 73% [25–29].

5. Conclusions & future recommendations

The current study examines the performance of a solar panel under different soiling and bird dropping conditions for Vellore's interior environment and provides insight into the impact of the panel's tilt angle, which was kept between 0° and 12.91°. In light of this, in the present work we addressed the energy efficiency of seven different types of samples, including black soil, desert soil, red soil, alluvial soil, laterite soil, coal dust, and bird droppings, dispersed across the PV panel at weights ranging from 10, 20, 30, 40, and 50 g. The key findings of this study, employing a solar photovoltaic simulator for indoor conditions, on power variation, efficiency, and loss efficiency of PV panels are summarized below.

- ➢ The physical properties of the samples play a major role in determining the efficiency of the PV panels. Bird droppings and coal dust were determined to show the highest and lowest influence on the thermal performance of PV panels, respectively regardless of the tilt angle. In addition, the performance of the PV panels was found to be less affected by the other types of soil particles.
- ➢ Maximum power drop of 3.43 W–0.63 W was observed in the case of Bird droppings when the weight is increased from 10 to 50 g. Consequently, minimum power drop of 4.75W–4.30W was seen for the coal dust when the sample concentration is varied from 10 to 50 g. For the tilt angle of 12.91°, the change followed the same trend like tilt angle 0°.
- ➢ Efficiency of the panel followed the same trend as that of variation in power. Bird droppings was found to have an efficiency drop from 2.9% to 0.5% in presence of 10 and 50 g respectively, coal dust has least efficiency change of 4.1% and 3.7% and the tilt angle was found to have a minor impact on the efficiency of the panel.
- ➢ Highest and lowest loss in efficiency was seen in the case of coal dust and bird droppings and the same were found to be 1.45% to 10.47% and 31.25%–86.53%, respectively in the presence of 10 g and 50 g of the samples and minor impact due to the tilt angle.
- ➢ The order of the soils from the lowest impact to highest impact on the power drop variation: coal dust, alluvial soil, black soil, laterite soil, red soil, desert soil, and bird droppings

The present study contributes to a better understanding of the impact of soil deposition on the performance of photovoltaic panels at various tilt angles in hot-dry region. Overall, it is essential to underline that bird droppings have a major influence on the significance of PV panels in hot-dry region. In contrast, coal dust represents the best scenario, as a minimal effect is revealed. This experimental simulation was conducted for Vellore, Tamil Nadu, India, which is located in a hot-dry region. The results can be generalised only for hot-dry climatic regions. Further studies need to be carried out to study the impact of various dust deposits in hot-humid, composite, temperate, and cold climatic regions.

Author statements

All authors have realized and accepted the data of the submitted manuscript. The paper presents unique work not earlier published in a similar form and not presently under consideration by another Journal. The authors followed ethical guidelines.

Credits author statement

Saboor Shaik: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. Pethurajan Vigneshwaran: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. Abin Roy: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. Karolos J. Kontoleon: Validation, Writing – original draft, Writing – review & editing. Domenico Mazzeo: Validation, Writing – original draft, Writing – review & editing. Erdem Cuce: Validation, Writing – original draft, Writing – review & editing. C Ahamed Saleel: Validation, Writing – original draft, Writing – review & editing. Mamdooh Alwetaishi: Validation, Writing – original draft, Writing – review & editing. Sher Afghan Khan: Validation, Writing – original draft, Writing – review & editing. Ali Etem Gürel: Validation, Writing – original draft, Writing – review & editing. Ümit Ağbulut: Validation, Writing – original draft, Writing – review & editing.

Table 4
IV characteristics of the panel at varied tilt angles.

	Dust Particles	I_{SC}		V_{OC}		I_{MAX}		V_{MAX}		Pmax	
		0	12.91	0	12.91	0	12.91	0	12.91	0	12.91
1	CLEAR PANEL	0.35	0.27	19.55	19.4	0.2975	0.2295	16.6175	16.49	4.943706	3.784455
2	BLACK SOIL 10	0.31	0.24	19.3	19.1	0.2635	0.204	16.405	16.235	4.322718	3.31194
3	BLACK SOIL 20	0.27	0.2	19	18.8	0.2295	0.17	16.15	15.98	3.706425	2.7166
4	BLACK SOIL 30	0.24	0.18	18.8	18.7	0.204	0.153	15.98	15.895	3.25992	2.431935
5	BLACK SOIL 40	0.2	0.16	18.7	18.6	0.17	0.136	15.895	15.81	2.70215	2.15016
6	BLACK SOIL 50	0.17	0.15	18.4	18.3	0.1445	0.1275	15.64	15.555	2.25998	1.983263
7	Red - 10	0.3	0.22	19	19.2	0.255	0.187	16.15	16.32	4.11825	3.05184
8	Red - 20	0.25	0.18	18.9	18.9	0.2125	0.153	16.065	16.065	3.413813	2.457945
9	Red - 30	0.22	0.16	19.2	18.9	0.187	0.136	16.32	16.065	3.05184	2.18484
10	Red - 40	0.18	0.14	18.6	18.8	0.153	0.119	15.81	15.98	2.41893	1.90162
11	Red - 50	0.15	0.12	18.6	18.5	0.1275	0.102	15.81	15.725	2.015775	1.60395
12	DESERT SOIL 10	0.28	0.22	19.4	19.2	0.238	0.187	16.49	16.32	3.92462	3.05184
13	DESERT SOIL 20	0.25	0.19	19.2	19	0.2125	0.1615	16.32	16.15	3.468	2.608225
14	DESERT SOIL 30	0.2	0.16	19	18.8	0.17	0.136	16.15	15.98	2.7455	2.17328
15	DESERT SOIL 40	0.19	0.14	18.8	18.6	0.1615	0.119	15.98	15.81	2.58077	1.88139
16	DESERT SOIL50	0.16	0.13	18.5	18.4	0.136	0.1105	15.725	15.64	2.1386	1.72822
17	Alluvial - 10	0.33	0.25	19.5	19.3	0.2805	0.2125	16.575	16.405	4.649288	3.486063
18	Alluvial - 20	0.33	0.25	19.5	19.3	0.2805	0.2125	16.575	16.405	4.649288	3.486063
19	Alluvial - 30	0.32	0.25	19.3	19.3	0.272	0.2125	16.405	16.405	4.46216	3.486063
20	Alluvial – 40	0.3	0.24	19.3	19.2	0.255	0.204	16.405	16.32	4.183275	3.32928
21	Alluvial - 50	0.3	0.24	19.2	19.1	0.255	0.204	16.32	16.235	4.1616	3.31194
22	Coal Dust 10	0.34	0.26	19.35	19	0.289	0.221	16.4475	16.15	4.753328	3.56915
23	Coal Dust 20	0.34	0.26	19	18.9	0.289	0.221	16.15	16.065	4.66735	3.550365
24	Coal Dust 30	0.33	0.26	18.9	18.9	0.2805	0.221	16.065	16.065	4.506233	3.550365
25	Coal Dust 40	0.32	0.25	18.7	18.5	0.272	0.2125	15.895	15.725	4.32344	3.341563
26	Coal Dust 50	0.32	0.25	18.6	18.5	0.272	0.2125	15.81	15.725	4.30032	3.341563
27	Laterite - 10	0.31	0.23	19.4	19.3	0.2635	0.1955	16.49	16.405	4.345115	3.207178
28	Laterite - 20	0.26	0.2	19.1	19	0.221	0.17	16.235	16.15	3.587935	2.7455
29	Laterite - 30	0.2	0.17	18.9	18.8	0.17	0.1445	16.065	15.98	2.73105	2.30911
30	Laterite - 40	0.17	0.14	18.8	18.7	0.1445	0.119	15.98	15.895	2.30911	1.891505
31	Laterite - 50	0.16	0.14	18.5	18.3	0.136	0.119	15.725	15.555	2.1386	1.851045
32	Bird Droppings - 10	0.25	0.17	19	18.7	0.2125	0.1445	16.15	15.895	3.431875	2.296828
33	Bird Droppings - 20	0.19	0.13	18.9	18.4	0.1615	0.1105	16.065	15.64	2.594498	1.72822
34	Bird Droppings - 30	0.13	0.11	18.2	17	0.1105	0.0935	15.47	14.45	1.709435	1.351075
35	Bird Droppings - 40	0.11	0.09	17.7	15.5	0.0935	0.0765	15.045	13.175	1.406708	1.007888
36	Bird Droppings - 50	0.07	0.05	12.5	10	0.0595	0.0425	10.625	8.5	0.632188	0.36125

Declaration of competing interest

We, the authors of this manuscript do not have any conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, our work.

Data availability

Data will be made available on request.

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