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Impact of Different Soiling Materials on Key Electrical Parameters of Photovoltaic Panels: An Experimental Analysis

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Abstract. Photovoltaic solar energy is currently one of the fastest-growing renewable energy sources and is expected to play a key role in enhancing resilience against climate change by contributing to global electricity generation. However, like any energy system, photovoltaic (PV) installations are subject to disturbances that can degrade their performance over their operational lifetime. One such disturbance, which has become a relevant research topic, is the soiling of PV panels. Environmental conditions, local climate, the type and properties of soiling materials, and even installation characteristics can significantly influence the accumulation of dirt on PV module surfaces. This paper presents an experimental study analyzing the adverse effects of different soiling materials on the performance of PV systems and their impact on key electrical parameters. The influence of six representative soiling materials was evaluated both at the single-module level and in a small grid-connected self-consumption PV installation. The results indicate that beach sand, commonly found in coastal and arid desert regions, causes the most severe performance degradation among the materials studied. While soiling primarily affects the current generated by PV modules, the results also show that array voltage can be significantly impacted in self-consumption grid-connected PV systems, leading to additional performance losses.

Key words. Soling, P-V curve, power losses, experimental analysis, maintenance activities

1. Introduction

In 2024, global photovoltaic (PV) investment reached a record USD 554 billion, accounting for 69% of total renewable energy investment. Annual installations rose to 601 GW, increasing cumulative global PV capacity to over 2.2 TW by early 2025, reinforcing photovoltaics as a central pillar of the global energy transition, [1], [2].

PV panels are designed for a guaranteed service life of 20–25 years, with an expected degradation of approximately 0.80% per year of their nominal power, [3]. However, several factors, including climatic variations, high solar cell temperatures, environmental exposure, and soiling, can accelerate performance losses and induce defects, increasing overall power degradation in PV systems.

Soiling is influenced by multiple factors, such as the local environment, climate, panel tilt and orientation, surface material, and the properties of the deposited material, [4]. Accumulated dust can cause defects such as potential-induced degradation (PID) or hot spots, [5], [6]. Variations in particle size, composition, light transmission, and panel surface temperature further affect PV performance, [6], [7], [8], while installation parameters such as tilt angle influence dust deposition and overall system efficiency, [9], [10]. The installation location also plays a critical role in soiling accumulation. For instance, in [11], six cities in northern Oman showed different levels of dust and pollution, highlighting the challenges for PV systems in desert and semi-desert regions. Similarly, [12] analyzed the impact of building materials on PV installations in Iraq, finding that ordinary and white cement caused the largest power losses, followed by sand and gypsum.

Modeling and simulating the impact of soiling is essential to understand how different materials affect PV performance at a specific site. Experimental measurements are a key component of this process, [12] [13], [14], [15]. Soiling not only reduces power output but also alters key electrical parameters, as reported in previous studies, [16]. Results show that soiling primarily affects the short-circuit current, with minimal impact on open-circuit voltage. Furthermore, it can modify the shape of I–V and P–V curves and influence local maximum power points, [17]. Understanding soiling types, their environmental interactions, and their effects on PV system performance is crucial for planning cleaning activities, optimizing cleaning frequency, and minimizing associated costs, [18].

This paper presents an experimental study analyzing the effects of six representative local soiling materials on PV system performance. Their influence was evaluated on key electrical parameters and P–V curves, both at the single-module level and in a small grid-connected self-consumption PV installation.

2. Soiling test methodology and case study

The impact of severe soiling on the performance of PV panels has been analyzed in two different ways. First, the effect of soiling was examined at the individual panel level. Second, the performance of a self-consumption PV array connected to the grid through a maximum power point tracker (MPPT) inverter was evaluated, where one of the panels within the array was affected by soiling. The PV array was composed of four panels connected in series. The manufacturer and model of the tested panel are Axitec AC-250P/156-60. This module is a 60-cell polycrystalline high-performance PV panel equipped with three bypass diodes, which divide the panel into three substrings of 20 cells each. The main electrical characteristics of the panel are presented in Table I. The tests were carried out outdoors under natural sunlight at the Renewable Energy Laboratory of the School of Engineering, University of Cádiz

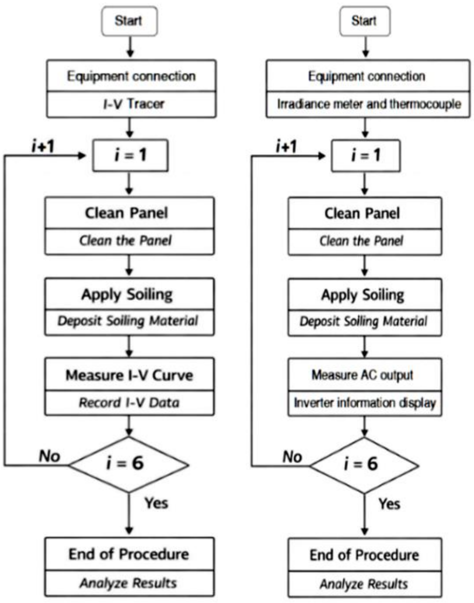
Table I. - Technical specifications of the PV module in STC

Manufacturer	AXITEC		
Model	AC-250P/156-60S		
Parameter	**Symbol**	**Value**	**Unit**
Maximum Power	Pmax	250.00+2%	Wp
Open-circuit Voltage	Voc	37.80	V
Short-circuit Current	Isc	8.71	A
Maximum Power Voltage	Vmp	30.70	V
Maximum Power Current	Imp	8.18	A

Table II. – Inverter technical data: DC input

Manufacturer	SMA	
Model	SB 1300TL	
Parameter	**Value**	**Unit**
Maximum input voltage	1400.00	Wp
MPPT voltage range	115 to 480	V
Minimum input voltage	100.00	V
Maximum input current	12.00	A

The procedures followed for the two analyses are illustrated in the diagrams presented in Fig. 1. Analysis 1, shown in Fig. 1(a), describes the soiling test methodology used to analyze the influence of soiling on a single panel. Analysis 2, shown in Fig. 1(b), presents the methodology used to evaluate the impact of soiling on the performance of a grid-connected PV array with an MPPT inverter, in which one of the panels within the array was affected by severe soiling.



a) b)

Fig. 1. Test methodologies: (a) Analysis 1: influence of severe soiling on a single panel; (b) Analysis 2: influence of severe soiling on a grid-connected PV array with an MPPT inverter.

A. First analysis: influence of soiling on a single panel.

For the first analysis, the equipment used to measure the electrical parameters of the PV module included an I–V tracer (HT I–V 400) and an irradiance meter (HT304N), shown in Fig. 2(a) and Fig. 2(b), respectively. Additionally, a contact temperature sensor (thermocouple) was used to measure the cell temperature at the back of the panel. Both the irradiance meter and the thermocouple were connected to the I–V tracer to allow the electrical parameters to be corrected to STC for more accurate comparison of results. In addition to recording the I–V and P–V curves, the measured electrical parameters included: maximum DC power (Pmax), open-circuit voltage (Voc), short-circuit current (Isc), voltage at maximum power point (Vmpp), current at maximum power point (Impp), and fill factor (FF).

Fig. 2. Measurement equipment used in Analysis 1: (a) I–V tracer HT I–V 400; (b) irradiance meter HT304N.

The soiling tests were performed for each material following a standard procedure: the panel was first cleaned, the soiling material was applied, and the electrical parameters were recorded. However, prior to the initial cleaning, the electrical parameters of the naturally dirty PV panel were measured. After cleaning, a reference measurement was taken with the cleaned panel to provide a baseline for comparison with the subsequent tests.

The cleaning process consisted of two steps: dry removal of powdered residues with a cloth to prevent reactions with water, followed by washing any remaining residue with distilled water.

Six soiling materials, denoted as *i* in Fig. 1, were evaluated: ash, albero sand, beach sand, clay, seawater, and cement. Two soiling methodologies were employed. In the first approach, the entire panel was uniformly subjected to severe soiling (Fig. 3). For each material, a total mass of 0.80 kg was deposited on the front surface of the panel. In the case of seawater, 0.3 L was sprayed uniformly over the panel surface. In the second approach, partial soiling was applied, targeting one cell per substring, as illustrated in Fig. 4. Under these conditions, 0.08 kg of soiling material was deposited directly onto the selected cells.

After the soiling material was deposited and a waiting period of 40 minutes, the I–V curve was obtained using the I–V tracer. All results were stored in the internal memory of the tracer. The procedure was then repeated for the next soiling material. In total, eleven measurements were performed: six with the entire panel soiled and five with partial soiling. The results were analyzed using the HT manufacturer software, TopView ©.

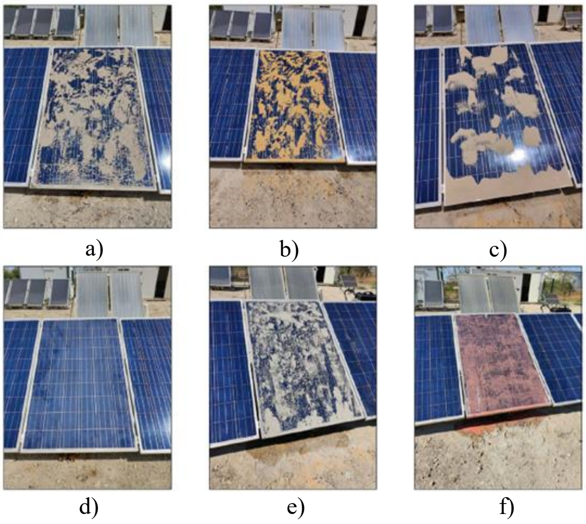


Fig. 3. PV panel under severe soiling for different materials: a) ash, b) albero sand, c) beach sand, d) seawater, e) cement and f) clay

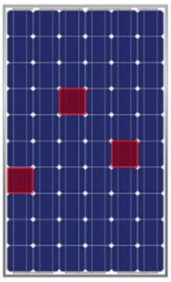


Fig. 4. PV panel cells partially soiled for each material: one cell per substring (three cells in total).

A generalized formulation is adopted to quantify the relative losses of the electrical parameters of the PV panel under soiling conditions. The relative loss of a given electrical parameter $\boldsymbol{X}$ is defined as:

$$Loss_{\mathrm{X}}(\%) = \frac{\mathrm{X}_{clean,STC} - \mathrm{X}_{i,STC}}{\mathrm{X}_{clean,STC}} x100 \qquad (1)$$

$$\mathrm{X} \in \{P_{max}, V_{oc}, V_{mpp}, I_{mpp}, I_{sc,} FF\} \qquad (2)$$

where all measured parameters were extrapolated to STC. The subscript $\boldsymbol{i}$ denotes the experimental result associated with each soiling material test, whereas the "clean" condition refers to the unsoiled reference state of the panel.

B. Second analysis: impact of soiling on the performance of a grid-connected PV array.

For the second analysis, the DC electrical parameters of the PV array were measured using the display of the grid-connected inverter. In this case, the I–V tracer was used to measure the irradiance and the operating temperature of the array through the irradiance meter and the thermocouple.

The soiling tests were performed similarly to the first analysis. For each soiling material, the procedure was as follows: the PV array was first cleaned, the soiling material was applied to one of the panels, and the DC electrical parameters were recorded. Prior to the tests, a reference measurement was taken with the cleaned array to provide a baseline for comparison with the subsequent tests.

As in the initial analysis, six soiling materials (Fig. 1) were used to soil one of the panels in the PV array (0.80 kg for solid materials and 0.3 L for seawater). Figure 5 illustrates the PV array with the panel subjected to soiling for a representative subset of the tested materials. A total of six measurements were conducted, during which the following DC electrical parameters were recorded: $\boldsymbol{P}_{\max}$, $\boldsymbol{V}_{\mathrm{mppt}}$, and $\boldsymbol{I}_{\mathrm{mppt}}$. It should be noted that these parameters correspond to the maximum power point tracked by the inverter. In addition, irradiance and cell temperature were also measured.

The following general formulation was used to quantify the relative performance losses of the PV panel's electrical parameters under soiling conditions

$$Loss_{\mathrm{X}}(\%) = \frac{\mathrm{X}_{clean,Theorical} - \mathrm{X}_{i,measured}}{\mathrm{X}_{clean,Theorical}} x100 \qquad (3)$$

$$\mathrm{X} \in \{P_{max}, V_{mpp}, I_{mpp}\} \qquad (4)$$

where $\mathbf{X}_{\boldsymbol{i,measured}}$ is the value of the electrical parameter measured during the tests for each soiling material, $\boldsymbol{i}$**,** and $\mathbf{X}_{\boldsymbol{clean,Theorical}}$ is the theoretical estimation of the electrical parameter for the clean array, calculated based on the irradiance and cell operating temperature for each test. The theoretical estimation was performed using a double-diode model of the panel simulated in MATLAB/Simulink ©.

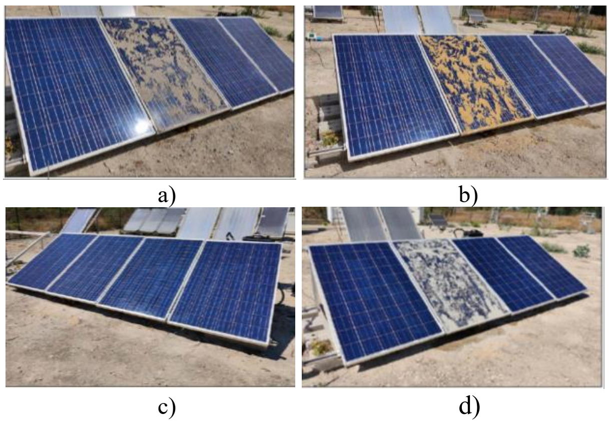


Fig. 5. PV panel subjected to soiling with different materials: (a) ash, (b) beach sand, (c) seawater, and (d) cement.

3. Results

This section presents the results obtained from the two analyses performed.

A. First analysis results: influence of soiling on a single panel.

The results regarding the influence of soiling on a single panel are summarized in Table II for the case of full-panel soiling, and in Table III for the case of partial soiling. The corresponding relative losses of the electrical parameters, calculated using Equation (1), are presented in Fig. 6 and Fig. 7, respectively.

In both cases, considering partial and full-panel soiling, beach sand, a material that can affect PV installations in coastal and desert areas, caused the greatest reduction in Pmax, decreasing it by 55.41% and 86.00%, respectively, compared to the Pmax of the clean panel. The panel with the smallest Pmax loss was that affected by seawater, an important factor in floating PV systems, which resulted in a loss of 1.40%, similar to the loss observed under natural soiling conditions, which was 2.93%. Except when the panel was soiled with clay, partial concentrations of soiling material produced a greater Pmax loss than full-panel soiling.

Regarding the remaining electrical parameters, and as shown in Figures 6 and 7, the reduction in Pmax is strongly correlated with losses in I_{mpp} and I_{sc}. In this case, V_{oc} remained essentially constant for all tested soiling materials, indicating that it is not significantly affected by soiling, unlike current, which is strongly impacted. Similar results have been reported by other authors (e.g., [17]), who concluded that soiling behaves similarly to a shading effect, potentially leading to the formation of hot spots under partial soiling conditions, which may arise even after light rainfall events.

Table II. – Results of the I-V tracer test in STC when the PV panel was completely affected by soiling for different materials

Soiling material	*Pmax* [W]	Voc [V]	Vmpp [V]	Impp [A]	Isc [A]	FF [%]
Clean panel	225.23	36.09	27.88	8.08	8.83	71.00
Natural dirty	218.64	36.02	27.80	7.86	8.48	72.00
Ash	138.55	35.73	30.73	4.51	6.05	64.00
Albero sand	125.83	35.80	32.44	3.88	6.12	57.00
Beach sand	100.43	35.95	32.23	3.12	4.67	60.00
Clay	129.22	35.73	30.52	4.23	4.99	72.00
Seawater	222.07	36.30	28.30	7.85	8.57	71.00
Cement	124.67	35.95	32.09	3.89	5.32	65.00

Table III. – Results of the I-V tracer test in STC when the PV panel was partially affected by soiling for different materials

Soiling material	Pmax [W]	Voc [V]	Vmpp [V]	Impp [A]	Isc [A]	FF [%]
Natural dirty	218.64	36.02	27.80	7.86	8.48	72.00
Ash	73.74	34.16	25.59	2.88	4.36	50.00
Albero sand	53.20	36.02	21.09	2.52	3.22	46.00
Beach sand	31.54	35.80	33.59	0.94	1.40	63.00
Clay	174.70	36.38	31.73	5.51	7.48	64.00
Cement	104.88	35.30	30.95	3.39	4.07	73.00

An interesting observation is the behaviour of Vmpp, whose values can be either higher or lower compared to the reference value measured for the clean panel. This is due to the presence of multiple local maximum power points in the panel's P–V curve. Because the panel is equipped with three bypass diodes, up to three local maximum power points can exist, and any of them may correspond to the global maximum power point. In this context, the degree of soiling on the PV cells in each substring of the panel determines the value of the global maximum power point.

Based on the results, it is not necessary for the entire panel to be fully soiled for these effects to occur. It is sufficient for a single cell within each substring to be affected by soiling, which may arise when dirt accumulates on the lower part of the panel due to gravity, impacting different cells. While this effect may be relatively minor when considering an individual panel in isolation, it can have a significant impact when a PV array is grid-connected through an MPPT inverter, as discussed in the following section.

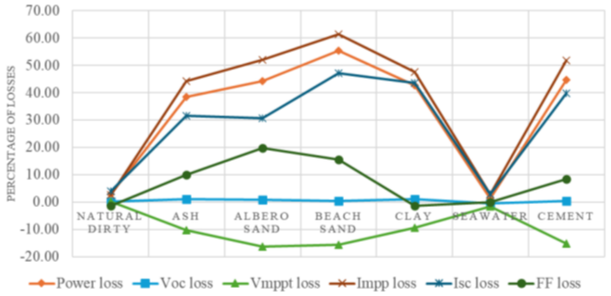


Fig. 6. Losses in electrical parameters of a PV panel under complete soiling conditions for different materials

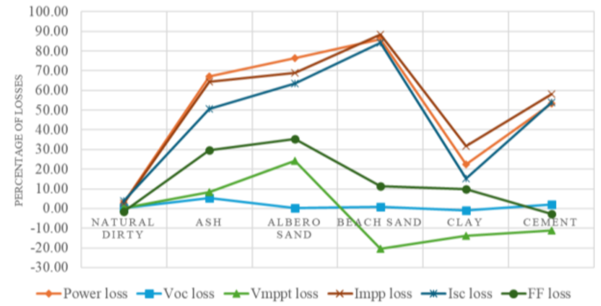


Fig. 7. Losses in electrical parameters of a PV panel under partial soiling conditions for different soiling materials

To facilitate a better understanding of these results and conclusions, Figures 8 and 9 present the resulting P–V curves when the PV panel was completely and partially affected by soiling, respectively.

B. Second analysis results: impact of soiling on the performance of a grid-connected PV array.

Measurement regarding the impact of soiling on the performance of a grid-connected PV array are summarized in Table IV. Then, the corresponding relative losses of the electrical parameters, calculated using Equation (3), are presented in Fig. 10. According to these results, the beach sand caused the largest reduction in Pmax, with a loss of 86.91%, making it the material with the greatest impact on array power. In this case, seawater was again the least damaging material; however, the power loss for the array increased to 25.91%.

Again, as observed in the first analysis, the reduction in Pmax was highly correlated with the decrease in I_{mpp}. This was not an expected result, since three panels in the array were not affected by soiling and all were protected by bypass diodes. The results show that this behaviour is attributable to the electrical configuration of the PV array and the DC input characteristics of the inverter, as illustrated in Figure 11, which compares the resulting V_{mpp} and Pmax with the inverter DC input conditions.

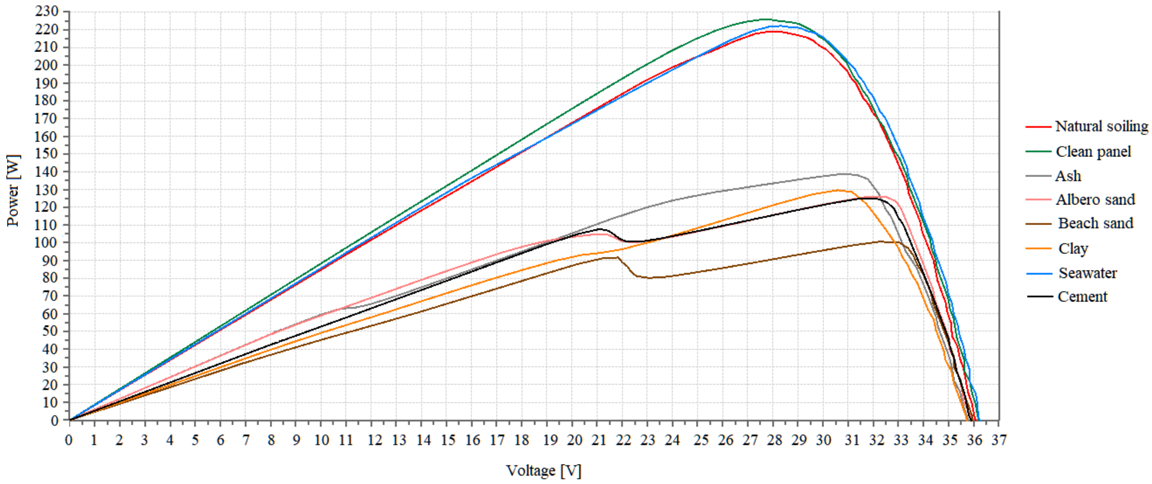


Fig. 8. P–V curves under fully soiled conditions

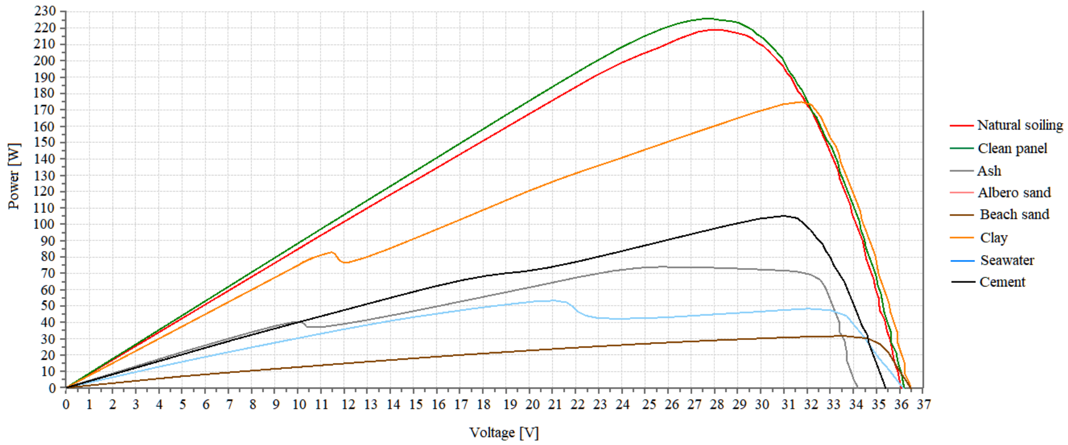


Fig. 9. P–V curves under partially soiled conditions

Table IV. – DC electrical parameter measurement of the PV array connected to the grid affected by several soiling materials

Soiling material	Pmax (W)	MPPT Voltage (V)	Impp (A)	Irrad. (W/m2)	Cell temp. (ºC)
Clean panel	813	101	8.05	970	46.2
Ash	279	102	2.74	859	42.7
Albero sand	360	110	3.27	887	45.3
Beach sand	109	107	1.02	916	48.2
Seawater	598	107	5.59	860	42.4
Clay	468	123	3.81	872	41.3
Cement	180	125	1.44	890	41.1

Under OPC at rated performance, the inverter operates within its Vmpp voltage limits, delivering high power output. However, under soiling, multiple local maximum power points can appear. In some cases, the global maximum power point occurs at a lower voltage than the original maximum, outside the MPPT voltage range of the inverter. As a result, the inverter may track a local maximum (with a greater voltage value) instead of the global maximum, leading to reduced power output. In certain cases, Vmpp can even exceed the reference (theoretical) value, as observed for cement and clay in Figure 10, which shows negative relative values.

Based on these results, soiling on PV panels affects both the current of the soiled panels and the voltage of the array. This can cause the inverter to operate outside its voltage limits, reducing the overall system performance more than expected.

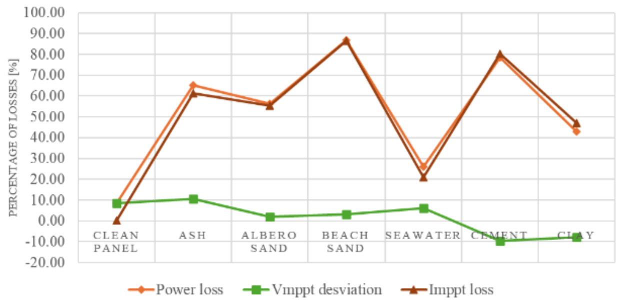


Fig. 10. Losses in electrical parameters of a PV panel under complete soiling conditions for different soiling materials

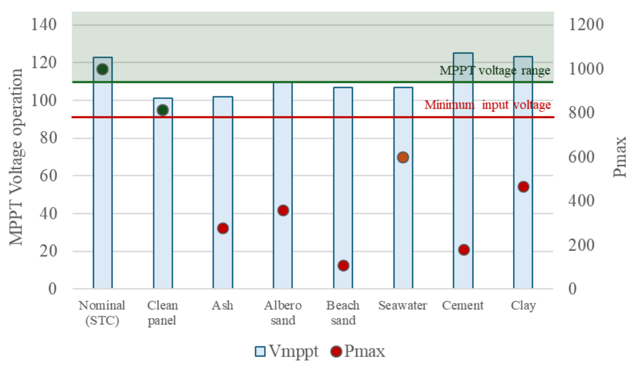


Fig. 11. Comparison of PV array resulted Pmax and V with DC input inverter characteristics under different soiling conditions.

4. Conclusion

This paper presents an experimental study on the impact of different soiling materials on the key electrical parameters of a single PV module and on a grid-connected PV array operating with an MPPT inverter. Six representative soiling materials were analyzed. Among them, beach sand, commonly found in coastal and arid desert regions, was identified as the material causing the most severe performance degradation, leading to power losses of up to 86.00% at the module level. In contrast, seawater exhibited the lowest impact on PV performance, reaching a maximum power loss of 25.91% at the array level.

The results indicate that electrical current is the parameter most strongly affected by soiling at the PV module level. However, when soiled panels are integrated into a grid-connected PV array with MPPT control, soiling affects not only the current of the impacted panels but also the overall array voltage. This interaction can lead to inverter operation outside its optimal voltage range and to inaccurate tracking of the global maximum power point, thereby reducing system performance beyond what would be expected from module-level analysis alone.

Despite the valuable experimental insights provided, this study presents certain limitations. The analysis is restricted to a limited set of soiling materials and discrete soiling conditions. Further research is needed to incorporate additional parameters, such as particle size, shape, mass, and adhesion properties, as well as to evaluate varying degrees of soiling (thickness) and their impact on optical transmission. One of the most relevant directions for future work is to examine the relationship between the optical transmission of each material, its deposition pattern on the panel (e.g., non-uniform or irregular distributions), and the resulting power output at the module and array level. Expanding the analysis to a broader range of soiling materials, including their physical characteristics, across different PV system configurations, would ultimately provide a more comprehensive understanding of soiling effects and its impact on power losses.

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