

Investigation on the Impact of Dust Types on Monocrystalline PV Module Performance in Malaysia

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How to cite this paper: Baharin, K.A., Ghazali, M.I. and Mat Zain, Z. (2025) Investigation on the Impact of Dust Types on Monocrystalline PV Module Performance in Malaysia. *Journal of Power and Energy Engineering*, 13, 133-147.
<https://doi.org/10.4236/jpee.2025.139009>

Received: August 11, 2025

Accepted: September 7, 2025

Published: September 10, 2025

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Abstract

Dust accumulation on photovoltaic (PV) panels significantly reduces energy output, particularly in areas with high particulate matter from natural or industrial sources. This study aims to evaluate the effects of sand, cement, and charcoal dust on short-circuit current (Isc), open-circuit voltage (Voc), and panel surface temperature, identifying which parameters are most affected and which dust types pose the greatest risk to efficiency. Controlled laboratory experiments were conducted with dust mass of 30 g, 40 g, and 50 g applied uniformly to PV panels, and performance metrics were measured relative to clean-panel baselines. Results indicate that Isc is highly sensitive to dust, with sand causing a 40% reduction at 30 g and up to 85% at 50 g, while cement and charcoal consistently cause severe 80% - 100% reductions at all weights. Voc remains largely stable, with only minor variations such as a 5% - 8% drop for cement at 40 g, confirming that current loss is the primary cause of power degradation. Panel temperature generally rises with dust, with charcoal showing the highest increase at heavier loads due to greater heat absorption. These findings underscore the importance of frequent cleaning and mitigation strategies in dust-prone environments, especially where fine industrial particulates are present.

Keywords

PV Performance, Dust Deposition, Power Loss Mitigation

1. Introduction

The global demand for clean and sustainable energy has accelerated the adoption

of photovoltaic (PV) technology as a key contributor to the renewable energy mix. However, the performance of PV modules is highly sensitive to environmental factors, with dust accumulation—commonly referred to as soiling—being a major cause of efficiency loss. Dust deposition reduces the amount of incident solar radiation reaching the PV cell surface, leading to decreased power output, hot-spot formation, and accelerated module degradation. Previous studies have shown that soiling can cause energy losses ranging from a few percent to over 40%, depending on the dust type, particle size, deposition density, and local climatic conditions [1]. In tropical climates, frequent rainfall is generally assumed to mitigate dust accumulation. However, in reality, tropical conditions often combine high humidity, intermittent rain, and airborne particulate matter from urban pollution, agricultural activities, or biomass burning, leading to rapid and sometimes adhesive dust deposition.

While much research has examined the effects of dust on PV modules, there remains a need for comparative assessments of different dust types under controlled conditions. Variations in particle morphology, density, and optical properties can significantly influence the degree of performance degradation. Understanding these differences is crucial for accurate performance prediction, site-specific maintenance scheduling, and the development of mitigation strategies.

Despite the known impact of soiling on PV performance, there is insufficient quantitative data comparing the effects of dust types with distinct physical properties—such as sand, cement, and charcoal—on key PV performance parameters. This study aims to investigate the influence of three distinct dust types—sand, cement, and charcoal—at varying deposition weights on the electrical output and operating temperature of PV modules.

2. Literature Review

Dust consists of microscopic solid inorganic and organic particles, typically 500 - 1000 μm in diameter, including soil particles, ash, and bacteria [2]. Its physical properties—such as size, shape, and density—affect how dust interacts with heat, light, and other environmental factors [3]. These interactions, in turn, can significantly influence the performance of PV systems.

2.1. Deposition of Dust on PV Modules

Dust deposition refers to the process by which airborne dust particles settle on a surface. This phenomenon is strongly influenced by particle characteristics and wind speed. Deposition rates are typically higher near the dust source and decrease with distance. On PV modules, three main types of deposition are identified based on their transport mechanisms:

- Dry deposition occurs without the involvement of water. Airborne particles are transported to the PV surface, where they adhere due to adhesive forces under dry conditions.
- Wet deposition involves airborne dust being captured and deposited by pre-

precipitation events such as fog, rain, or snow.

- Intermediate deposition occurs when dusty air mixes with clouds or fog containing water droplets before settling.

The rate of soiling depends on dust particle size: fine particles ($<1\ \mu\text{m}$) tend to settle and accumulate more rapidly than coarse particles ($>5\ \mu\text{m}$) [2].

Another important factor influencing dust accumulation on PV modules is surface quality. The accumulation rate varies with different surface materials and coatings. Surfaces with protective coatings generally experience less dust settlement than uncoated surfaces. Dust tends to build up more quickly on PV surfaces made of plastics or epoxy compared to glass. Additionally, wind effects on dust buildup vary by location and depend on both dust characteristics and wind velocity. In some cases, wind striking a PV module at a particular orientation and tilt angle can reduce the rate of dust accumulation [2].

2.2. Impact of Dust on PV Modules

Although solar PV systems provide substantial long-term benefits, their performance can be significantly impaired by soiling—the accumulation of dust and other particulates on panel surfaces. While material aging over a 25-year lifespan can cause up to a 20% reduction in output, soiling alone may reduce generation by over 30% within weeks [4]. Dust particles, typically $<500\ \mu\text{m}$ in diameter, vary in composition (e.g., silica, ash, red soil, sand, calcium carbonate) and affect performance depending on their mass and size distribution. Greater deposition mass leads to higher losses, and smaller particles are particularly detrimental as they block more sunlight. Even short-term exposure without cleaning (two months) can reduce energy yield by $\sim 6.5\%$, while desert conditions may cause efficiency drops of up to 40% [5].

Experimental studies highlight the role of particle type and size. In Badarpur, India, Athar *et al.* [6] reported maximum power losses at $650 - 850\ \text{W/m}^2$ of 59% - 62% for sand (50 g), 42% - 43% for fly ash (25 g), 72% - 76% for rice husk (25 g), 36% - 47% for chalk powder (25 g), and 55% - 58% for brick powder (25 g). El-Shobokshy *et al.* [7] showed that finer particles caused greater losses, with carbon ($5\ \mu\text{m}$) reducing output by up to 90%, compared to 40% for coarser cement particles ($10\ \mu\text{m}$) at the same surface mass density. Similarly, Jiang *et al.* [8] found that increasing dust deposition from 0 to $22\ \text{g/m}^2$ resulted in 0% - 26% efficiency loss across thin-film amorphous silicon, polycrystalline silicon (epoxy surface), and monocrystalline silicon (glass surface) modules.

2.3. Dust Properties on PV Surface

Dust consists of microscopic solid inorganic and organic particles, typically $500 - 1000\ \mu\text{m}$ in diameter, including soil particles, ash, and bacteria [2]. Its physical properties—such as size, shape, and density—affect how dust interacts with heat, light, and other environmental factors [3]. These interactions, in turn, can significantly influence the performance of PV systems. In particular, the dust block sun-

shine from reaching the module internal material, thus not triggering the movement of electrons.

2.3.1. Dust Size

Dust accumulating on the surface of photovoltaic (PV) panels varies in dimension and is generally referred to as dust particle size. These particles can range from submicrometer to millimeter scale, with variations in shape, volume, and chemical composition. The particle size distribution of dust has been reported to range from as small as 0.003 μm for clay particles to 190 μm for soil particles, with the majority (83%) falling between 0.3 and 60 μm [9]. Experimental studies have shown dust sizes ranging from 0.1 to 1000 μm , with most collected particles (43%) between 100 and 500 μm , and 15% between 10 and 50 μm [10]. Dust deposition also differs between normal conditions and dust storm events, with dust storms typically producing smaller particles—often in the range of 1.1 to 1.2 μm . Dust particle size is a key factor influencing PV performance [11]. Smaller particles are more likely to accumulate on PV surfaces as they are easily transported by wind. Moreover, due to their higher surface coverage, fine particles can block more incident sunlight than larger particles, thus having a greater negative effect on solar energy transmission [12].

2.3.2. Dust Shape

Dust particles can vary in shape from spherical to highly irregular, with their form largely determined by their origin and the environmental conditions in which they are produced. This also influences their chemical composition. For example, desert dust particles are often angular and irregular, while industrial dust may vary in shape depending on the manufacturing process [13]. The weight and shape of dust have a clear impact on both the deposition process and PV efficiency. Irregularly shaped particles can roughen the panel surface, increase adhesion and make cleaning more difficult [14]. This, in turn, reduces the amount of sunlight reaching the PV surface and lowers overall performance.

Irregularly shaped particles can have a greater effect on PV performance than spherical particles of the same size [15]. Smooth, round particles are less likely to adhere to the panel surface and are generally easier to remove, while irregularly shaped particles tend to lodge more firmly and resist cleaning [2]. It is important to note that dust characteristics, including shape, vary depending on location and surrounding conditions. Since particle shape affects how dust interacts with light and heat, as well as how it settles and accumulates, understanding these properties in specific environments is essential for developing effective strategies to minimize dust-related performance losses.

2.3.3. Dust Density

Dust deposition density refers to the mass of dust particles per unit area on a PV panel surface. This accumulation can significantly affect panel performance by reducing the amount of sunlight reaching the cells [16]. As dust deposition density increases, the PV panel's ability to generate electricity decreases. For example,

studies have shown that a dust deposition of 0.5 g/m^2 can reduce PV module performance by about 8.5%, while a density of 2 g/m^2 can cause a 20% drop. High dust densities can also create shading, leading to hot spots and further reducing overall efficiency [17].

2.3.4. Other Environmental Factors

An environmental factor is a measurable aspect of the surroundings that influences the growth, survival, or functionality of an organism. It refers to any element that alters the natural environment. Here, two main factors are discussed.

Wind, defined as the movement of atmospheric air, is a key environmental factor affecting dust distribution on PV modules. Its velocity can range from gentle to powerful. It is capable of transporting heavy debris and generating noise. Wind plays a dual role in both depositing and removing dust, with its effect depending on particle size and wind speed [18]. Wind speed also influences dust settlement, lower speeds generally result in reduced deposition and minimal impact on PV output, whereas higher speeds promote greater particle accumulation and can alter the structure of the dust layer.

Another factor is humidity, defined as the amount of water vapor present in the atmosphere [19]. It is equally important in determining dust characteristics and deposition behaviour on PV modules. High humidity or the presence of morning dew can cause the dust layer to absorb moisture, forming droplets of salt solution that trap insoluble particles. Increased relative humidity promotes adhesion between dust particles, leading to sticky deposits on the PV surface. In mounted PV modules, humidity can replicate the effects of dew formation, thereby accelerating dust accumulation [20].

3. Methodology

This experimental-based study plans to investigate the impact of three different types of dust—sand, cement and charcoal—on the electrical performance of monocrystalline PV modules. These dust types represent a diverse, realistic spectrum of dust pollution that can potentially affect PV systems across different types of environments, ranging from rural, urban and industrial settings.

Sand is common for areas near coastal zones. Since part of Malaysia is a peninsular, many PV installations with good solar potential are located near the sea. Even if the PV system is not in proximity, sand can easily accumulate on PV surfaces due to the wind. Sand also represents coarse ($100 - 1000 \mu\text{m}$), low-adhesion dust which provides a useful benchmark for low-density surface coverage.

Meanwhile, cement dust is a common construction-related pollution. It is prevalent in urban areas and near building construction where rooftop PV installations are growing rapidly. They represent fine particulate dust that attaches strongly to PV surfaces. Interaction with rainwater or moisture can be more detrimental on PV surfaces as it forms a dense, semi-opaque layer that blocks sunlight and not easy to clean.

The final type, charcoal, mimics urban particulate pollution due to its small size ($<100\text{ }\mu\text{m}$). Charcoal dust results from biomass combustion, open burning of waste or industrial emissions. Its dark colour and absorptive properties have significant potential to block sunlight more severely and increase surface heating of PV modules. It is also difficult to clean after smearing.

The steps taken follows the process shown in **Figure 1** while the equipment and items used are shown in **Figure 2**. First the dusts are refined using a flour strainer to produce particle sizes typically less than $300\text{ }\mu\text{m}$, with most falling in the range between $10 - 100\text{ }\mu\text{m}$. Then, they are weighted into three types, namely 30 g, 40 g, and 50 g, which are then separated into containers.

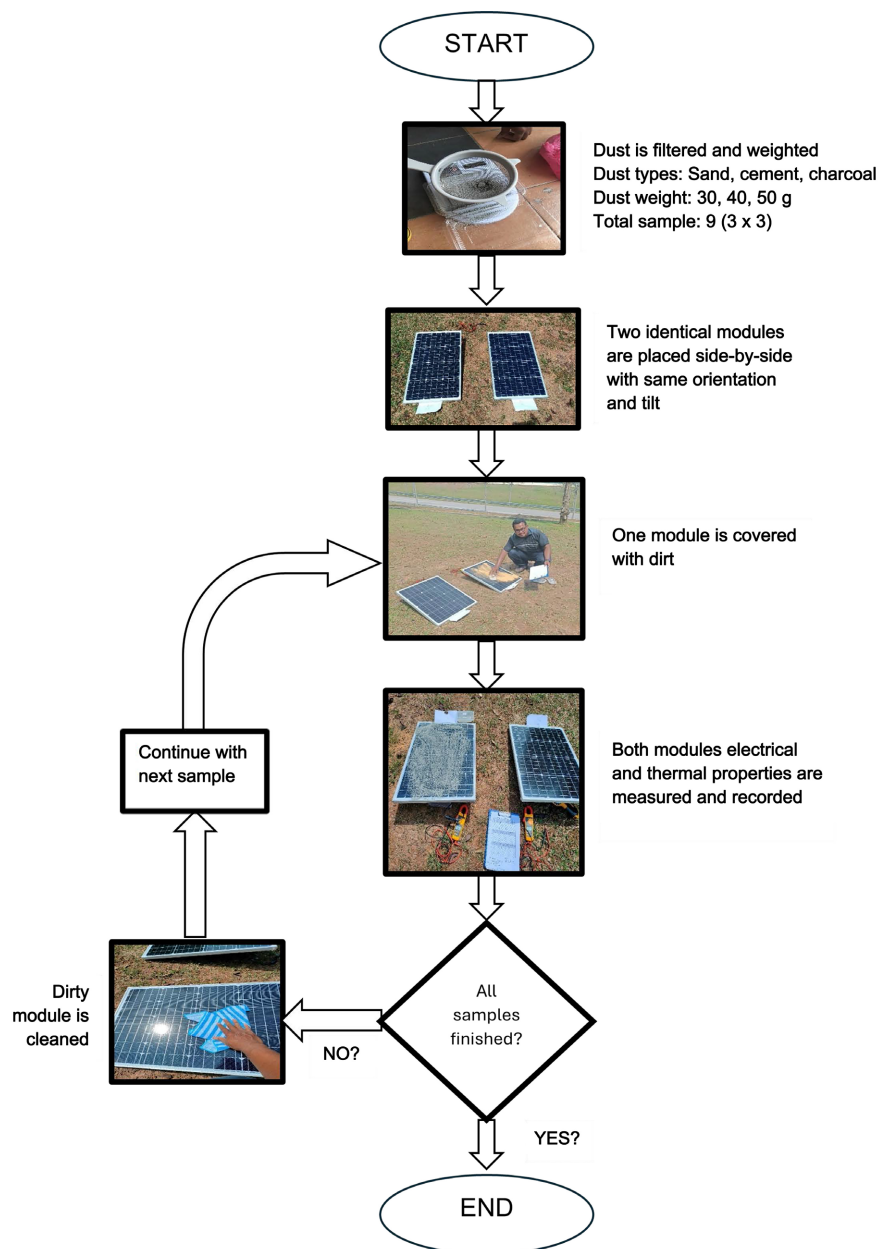


Figure 1. Sequence of methodology process.



Figure 2. Equipment/material used for the experiment.

Next, two identical, thoroughly cleaned monocrystalline PV modules are placed in an open environment side-by-side with the same orientation and tilt angle so that both are exposed to the same amount of solar irradiance. One module that will always remain clean serves as the control unit while the other functions as the test unit where dust will be applied. Prior to testing, baseline measurements of I_{sc} , V_{oc} and module surface temperature are recorded under clean conditions for reference.

The key environmental conditions during the tests are as follows:

- Typical Irradiance—(400 to 700 W/m²)
- Ambient temperature—(28°C to 32°C)
- Relative Humidity—(75% to 80%)

Overall, nine samples are tested—three weight levels for each of the three dust types. For each test, the dust is evenly distributed over the whole surface of the test unit to simulate realistic soiling conditions. The control unit remains clean throughout all the tests to provide a direct performance comparison. After the dust is scattered on the module, a few minutes are given to allow the sunlight to stabilize. Then, the I_{sc} , V_{oc} and surface temperature of both modules are measured and recorded.

Once each test is finished, the dust is carefully removed from the test module, and the module is cleaned to return it to baseline condition before applying the next sample. This process is repeated until all the samples are finished.

After the experiment is completed, the percentage of decrease in I_{sc} and V_{oc} as well as the percentage of increase in surface temperature due to dust deposition is calculated and analysed. Since the modules are not connected to any loads, power cannot be directly measured. Therefore, reductions in I_{sc} will be used as a proxy to observe performance degradation, assuming irradiance remains relatively stable. Variations in I_{sc} are expected to be more indicative of light-blocking effects caused by dust, while V_{oc} changes may reveal impacts related to surface temperature.

4. Results and Discussion

The amount of sunlight that reaches the surface has a significant impact on how

well photovoltaic (PV) modules work. One of the most frequent environmental conditions that lowers this irradiance is dust collection, which forms a physical barrier between the PV cells and the sunlight. An identical monocrystalline PV module was subjected to three different types of dust (30 g, 40 g, and 50 g) in order to examine the effects of each on the electrical parameters of the module, specifically the open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}), while it was exposed to natural sunlight. Throughout the experiment, a clean PV module served as a control to allow for a direct comparison of performance. To assess potential thermal impacts brought on by the different forms of dust, surface temperature readings were also taken. The results presented in this section detail the variation in V_{oc} , I_{sc} , and module surface temperature for each dust type and mass, followed by a comparative analysis to identify the dust characteristics most detrimental to PV performance.

4.1. Dust Impact to Irradiance on PV Module and I_{sc}

Figure 3 shows the effect of dust on irradiance and I_{sc} measured over a specified duration of time. The red line represents the current on the clean module while the rest is the current on the test module. Regardless of the type of dust, the current drops dramatically once the test module is covered. However, comparing the three dusts at 30 g, the modules with sand perform slightly better compared with the other two while cement has the worst performance. Still, all types of dust affect the I_{sc} severely. Comparison across different dust weights yield that as the weight increase, I_{sc} becomes almost zero. At 50 g, there is virtually no difference

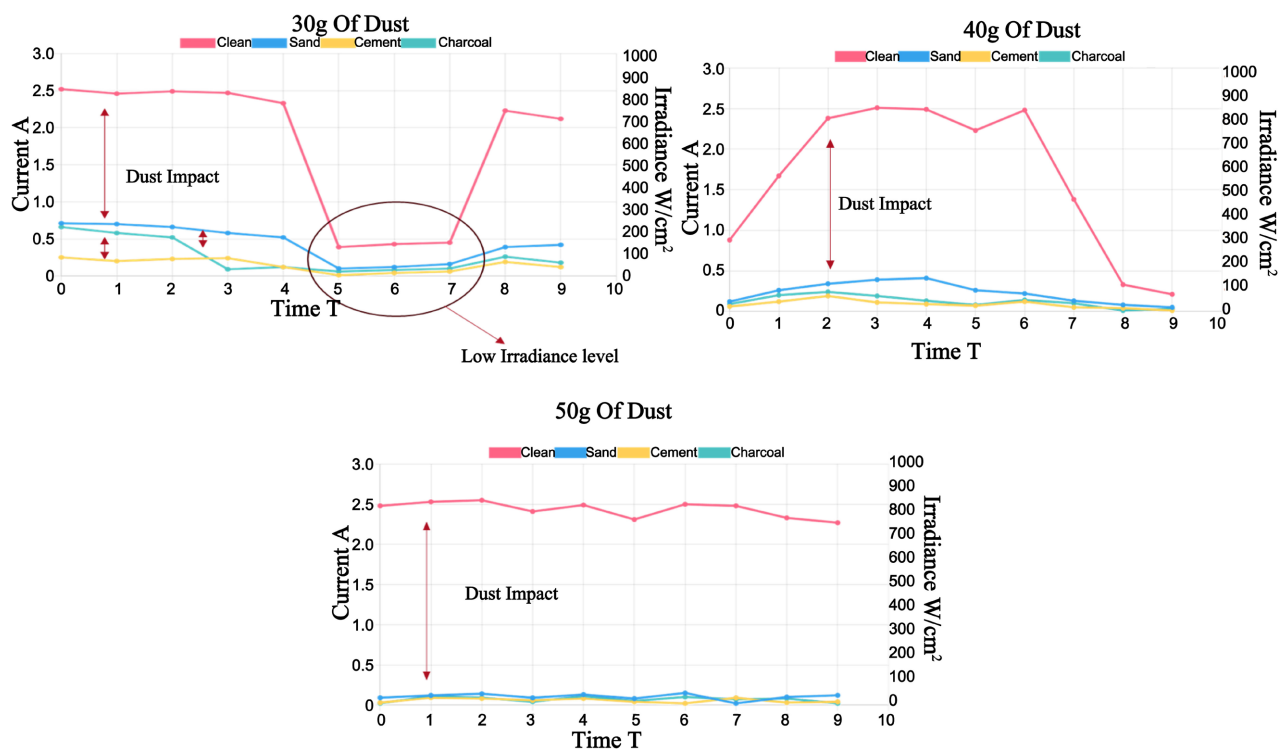


Figure 3. Instantaneous impact of dust on irradiance and I_{sc} .

on the dust type on Isc performance. This is a direct indication that the dusts block sunlight from reaching the module internal material thus not triggering the charge movement within the module.

The correlation between Isc for the control and test modules can be observed in **Figure 4**. Across all dust types and masses, the Isc of the dusty PV module is significantly lower than that of the clean module. This confirms that dust accumulation causes substantial optical shading, reducing the amount of light reaching the solar cells and thereby decreasing photocurrent generation.

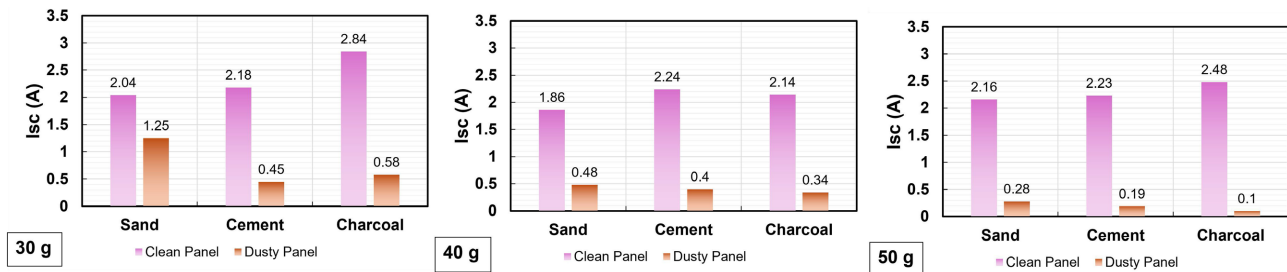


Figure 4. Correlation between Isc for clean and dusty panels.

As dust mass increases from 30 g to 50 g, Isc drops progressively for all dust types. The most dramatic reductions occur at 50 g, where Isc values fall below 0.3 A for all dust types, compared to more than 2 A for the clean module. This suggests that heavier dust loads result in denser and more opaque surface coverage, amplifying shading effects and further limiting light penetration.

Charcoal consistently shows the largest drop in Isc. For example, at 30 g, Isc drops from 2.84 A to 0.58 A, roughly an 80% reduction. At 50 g, the degradation is even worse at 0.10 A, approximately 96%. This can be related to the physical properties of charcoal—its small particle size, dark colour and high surface coverage, which block sunlight and increase surface heating. Cement causes the second-highest reduction. Its fine, light-grey particles adhere well to the module surface and form an opaque layer, causing strong light attenuation even at lower masses. Sand has the least severe effect among the three but still causes large reductions at higher masses. This is likely due to its larger particle size, which leaves more gaps for light transmission compared to cement and charcoal.

As for the relative sensitivity due to dust mass, the Isc drop for sand at 30 g (1.25 A) and 50 g (0.28 A) is large but somewhat gradual, reflecting the less cohesive nature of sand particles. For cement and charcoal, the reduction is sharper with increasing mass, especially between 40 g and 50 g, where the fine particles quickly reach near-complete coverage.

If the heaviest mass is considered, with 50 g of charcoal dust, Isc is reduced to less than 5% of its clean panel value. For cement dust, it's less than 10%. Even for the least damaging dust type, sand, reduces Isc to about 13% of its clean value at 50 g. This highlights that in heavily soiled environments, PV modules can lose 85% - 95% of their Isc if not cleaned regularly.

4.2. Dust Impact on Module Surface Temperature

Correlation results from **Figure 5** indicate that across all dust types and masses, dusty PV modules tend to operate at higher temperatures compared to clean panels. This is expected because dust reduces light transmission to the cells, causing more energy to be absorbed as heat rather than converted into electrical energy. For sand and cement, the difference in temperature between clean and dusty panels is relatively small at higher dust masses (40 g and 50 g), likely because both surfaces are already absorbing and retaining significant heat at these levels.

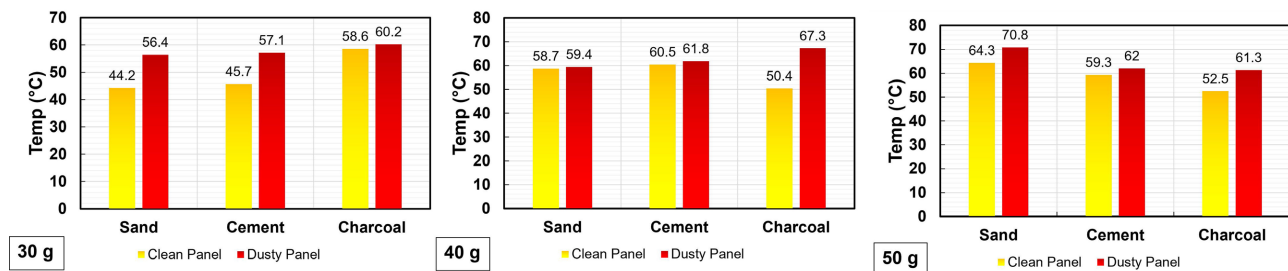


Figure 5. Correlation between module surface temperature for clean and dusty panel.

For charcoal, temperature increases are more pronounced, particularly at 30 g and 40 g, with up to about 17°C difference at 40 g (50.4°C clean vs. 67.3°C dusty). Charcoal generally causes the largest temperature to rise for dusty panels at lower dust masses (30 g and 40 g). Its black colour and high absorptivity significantly increase surface heat gain, especially before dust mass becomes so high that air-flow cooling differences diminish. Sand shows the highest dusty panel temperature at 50 g (70.8°C), even higher than charcoal at that mass. This could be due to sand's larger grain size, which may reduce convective cooling by trapping more stagnant hot air above the surface. Larger particles such as sand grains tend to form a more uneven and porous surface layer compared to finer dust. This rougher surface can trap small pockets of air between the particles and the module surface. Because air is a poor conductor of heat, these trapped pockets create a layer of thermal insulation, reducing convective cooling between the hot module surface and the surrounding airflow. Cement has intermediate effects, with moderate heating likely due to its lighter colour and lower absorptivity compared to charcoal.

There are some notable nonlinear trends. At 30 g, the heating effect is strongly dependent on dust type (largest differences between clean and dusty panels). At 40 g, the gap narrows for sand and cement but remains large for charcoal. At 50 g, differences between clean and dusty panels become smaller for cement and charcoal, possibly due to a thermal saturation effect where both surfaces are already near maximum heating under full sunlight.

The patterns here complement the I_{sc} trends from the previous section. Higher temperatures generally correspond to lower I_{sc} values because excessive heat increases semiconductor resistance and reduces the PV cell voltage. Charcoal's com-

bination of high heating and strong optical shading makes it the most detrimental dust type overall.

4.3. Dust Impact on Voc

General observation of the impact of dust on Voc, shown in **Figure 6** indicate that the reduction in Voc is almost negligible. Across all dust types and masses, the voltage drop is in the range of roughly 0.2 - 1.2 V, which translates to about 1% - 6% loss.

At 30 g, the largest relative Voc drop occurs for sand (−1.2 V), followed by cement (−0.7 V) and charcoal (−0.2 V). At 40 g, all dust types show smaller voltage drops (≤ 0.5 V), indicating that the impact of dust on Voc does not increase linearly with dust mass. Meanwhile, at 50 g, the voltage differences between clean and dusty panels are minimal (≤ 0.5 V), suggesting that at high dust loading, the Voc drop reaches a saturation point.

Sand tends to cause slightly larger Voc reductions at lower masses (30 g), possibly due to its higher surface coverage and scattering effects compared to finer charcoal dust. Charcoal, despite causing severe Isc drops, has the least impact on Voc, which aligns with PV theory—Voc is less sensitive to irradiance than Isc.

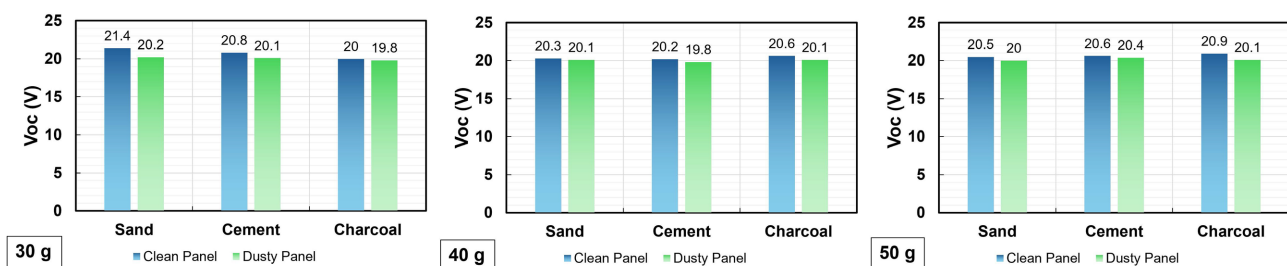


Figure 6. Correlation between Voc for clean and dusty panel.

4.4. Synthesis of Results

A summary of all the data recorded throughout the experiment is shown in **Table 1**. It highlights some key findings. The data clearly shows that dust accumulation significantly reduces the short-circuit current (Isc) of photovoltaic panels, making it the main driver of performance loss, while the open-circuit voltage (Voc) is minimally affected. Sand causes a moderate Isc drop of about 38.7% at 30 g but becomes highly detrimental at heavier loads, reaching an 87% reduction at 50 g. Cement and charcoal, however, cause severe Isc losses even at low dust weights, with cement showing around 79.4% drop at 30 g and charcoal about 79.6%, both worsening to over 84% - 96% at 50 g. Voc remains relatively stable for all dust types, with the largest drop being 8% for cement at 40 g. Dust also increases panel temperature due to reduced cooling and increased heat retention, with sand causing the highest temperature rise at low dust load (38.7% at 30 g) and charcoal showing a substantial increase at higher weights (16.7% at 50 g), likely due to its darker colour absorbing more heat. Overall, charcoal dust is the most damaging,

as it consistently causes extreme current reduction and significant temperature rise; cement is similarly harmful in terms of current loss but with less temperature impact, while sand is less harmful initially but still leads to severe performance loss at heavier deposition. These findings highlight the importance of frequent cleaning in environments with fine particulate dust such as cement and charcoal to prevent drastic power output losses.

Table 1. Summarised results of the experiment.

Dust weight	Dust type	Clean panel			Dusty panel			% Decreased		% Increased
		Voc (V)	Isc (A)	T (°C)	Voc (V)	Isc (A)	T (°C)	Voc (%)	Isc (%)	
30 g	Sand	21.4	2.04	44.2	20.2	1.25	56.4	5.6	38.7	38.7
	Cement	20.8	2.18	45.7	20.1	0.45	57.1	3.4	79.4	24.8
	Charcoal	20	2.84	58.6	19.8	0.58	60.2	1	79.6	2.7
40 g	Sand	20.3	1.86	58.7	20.1	0.48	59.4	0.49	74	1.2
	Cement	20.2	2.24	60.5	19.8	0.40	61.8	5.9	80	2.2
	Charcoal	20.6	2.14	50.4	20.1	0.34	67.3	2.43	84	33.7
50 g	Sand	20.5	2.16	64.3	20	0.28	70.8	2.4	87	10.1
	Cement	20.6	2.23	59.3	20.4	0.19	62.0	0.9	91	4.5
	Charcoal	20.9	2.48	52.5	20.1	0.1	61.3	3.8	96	16.7

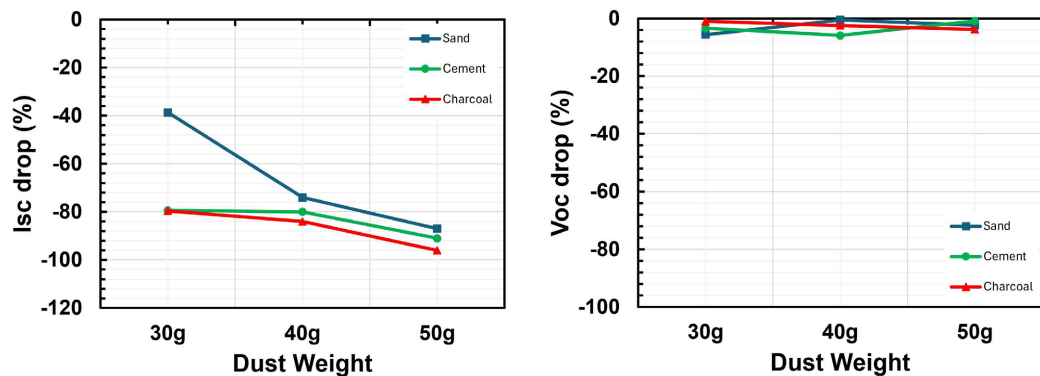


Figure 7. Percentage of Isc and Voc decrease across dust weights.

The graph shown in **Figure 7** show the Isc and Voc drop in percentage corresponding to each dust type with increasing weights. Dust accumulation on photovoltaic panels primarily affects the short-circuit current (Isc), with minimal impact on the open-circuit voltage (Voc). Sand causes a moderate Isc drop of about 40% at 30 g but worsens sharply to around 85% at 50 g, while cement and charcoal consistently cause severe losses of 80% - 100% across all dust weights. Voc remains largely stable for all dust types, with only slight variations, such as a small 5% - 8% dip for cement at 40 g and near-flat changes for sand and charcoal. This indicates that Isc drop, rather than Voc drop, is the dominant factor in performance reduction, with cement and charcoal causing immediate and substantial losses even at

low dust levels, while sand shows a gradual but significant impact as dust load increases. In dust-prone areas, especially near construction or industrial zones, panels exposed to cement or charcoal particles will experience rapid power loss, as stable voltage cannot offset the sharp current reduction.

5. Conclusions

The findings clearly demonstrate that dust accumulation significantly impacts photovoltaic panel performance, with the short-circuit current (I_{sc}) being far more sensitive to dust than the open-circuit voltage (V_{oc}). Sand shows a moderate impact at low dust loads, with about a 40% drop at 30 g, but its effect intensifies drastically to approximately 85% at 50 g. Cement and charcoal, on the other hand, cause severe I_{sc} reductions of 80% - 100% across all dust weights, indicating that even minimal deposition can result in major performance losses. V_{oc} remains relatively stable across all dust types, with only minor fluctuations such as a small dip for cement at 40 g, confirming that current loss—not voltage reduction—is the primary driver of power degradation.

From a practical perspective, these results highlight the urgent need for targeted maintenance strategies in dust-prone areas. In environments with high levels of fine particulate matter, such as cement or charcoal dust from industrial or construction activities, photovoltaic systems are at risk of rapid and substantial power output decline. While sand is less harmful initially, it still causes significant losses at higher dust loads, underscoring the importance of regular cleaning schedules regardless of dust type. Ultimately, ensuring optimal panel performance in such conditions requires preventive measures, including site-specific cleaning intervals and possibly the use of dust-resistant coatings or protective barriers. Sites near coastal areas where wind gusts are common and sites near an active construction site may require more frequent and thorough cleaning process to avoid severe power drop.

Future work shall focus on expanding the study to include a wider range of dust types, particle sizes, and compositions to better understand their individual and combined effects on photovoltaic performance. This study only provides a short-term, instantaneous degradation through experimental work. Therefore, a long-term outdoor testing under real environmental conditions is suggested for future work as it would provide more accurate insights into the rate of dust accumulation and its seasonal variations. Additionally, investigating the impact of dust on overall energy yield, thermal behaviour, and panel degradation over time could help in developing predictive maintenance models. Research into effective mitigation strategies, such as self-cleaning coatings, anti-static surfaces, or automated cleaning systems, would also be valuable in reducing dust-related losses and ensuring sustained PV efficiency in diverse operating environments.

Acknowledgements

The authors would like to thank the Centre for Research and Innovation Manage-

ment (CRIM), Universiti Teknikal Malaysia Melaka for supporting this research work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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