The influence of dust physical specifications photovoltaic modules performance

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Abstract
In this article, an experimental analysis was performed to assess the effect of dust accumulation on PV modules resulting energy losses. The dust used in the experiments was collected from three specific sites in the Republic of Iraq. Samples of pollen and common dust were collected from three sites for a period of three months in order to assess their physical properties.
The results showed that 64% of all dust particles are 2 to 62 μm in diameter. The effect of dust deposition on the PV modules has mixed results from one location to another. The surface mass of the precipitated dust is concentrated on the PV unit only (up to 5 g/m²/day), and the decrease in the energy results was evident. The daily maximum decrease in efficacy was 0.05% for the samples examined, and when compared to neighboring countries its value is clear and effective. The results showed that the exposure of the photovoltaic cells to external conditions for a period longer than two months caused a decrease in the productivity of the photovoltaic unit by 35-40%. Therefore, it is recommended that there be periods of cleaning the cells up to two months. The study concluded that the use of PV systems in the studied sites is a practical and economical option.

Keywords: Dust deposition; pollutant type; physical properties; photovoltaic

1. Introduction
Heavy and prolonged dependence on fossil fuels, especially oil, causes significant pollution to the environment that is difficult to dissolve. One of the most important solutions to environmental pollution resulting from burning fossil fuels is the use of photovoltaic systems to produce electrical energy [1]. The shift towards such systems will reduce the consumption of fossil fuels, especially oil, which means protecting the economic security of many countries in the world, and in particular those imported oil [2]. PV systems today generate very high capacities of up to megawatts, and the efficiency of photovoltaic panels has begun to rise, currently reaching 20%, and is expected to reach 40% soon [5]. Various studies have examined the potential of photovoltaic cells in lighting and operating medical clinics in remote areas of the network [4], water pumping [5, 6], electronic towers for communication [7] car parking and street lighting systems [8]. Many factors affect the efficiency of photovoltaic systems such as: Geographical location and topography, the photovoltaic panel tilt angle from the horizon, the technology made of the photovoltaic panels, and the most important of these factors are environmental conditions [9]. Since the PV system is installed in the open air, it is subject to sometimes extreme weather conditions such as solar irradiation [10], relative humidity [11, 12], wind blowing [13], ambient temperature [14] in addition to the deposition of dust and airborne pollutants on solar panels [15]. Because of the importance of the last factor, the effect of dust on the performance of PV systems has been studied extensively in recent years [16]. The studies focused on everything related to dust and its components, such as the physical properties (the size of dust particles, their shapes, and their components) [17, 18], and on the chemical properties of dust (such as the type and chemistry of dust-forming materials) [19]. Numerous studies have explored the
influences that affect the performance of photovoltaic systems and have been particularly concerned with the accumulation of dust, especially in areas of the solar belt with high solar radiation, most of which are desert areas [20]. References [21, 22] examined the effect of deposited dust in several regions of Iraq on the electrical performance of PV systems. Ref. [21] studied the dust deposited from four regions in Iraq in terms of its components and the effect of these dust components on the performance of the photoelectric systems. As for Ref. [22], he examined the effect of certain substances found in dust components (cement, carbon particles, and limestone) on the electrical efficiency of a photoelectric system installed in Baghdad, the capital of Iraq.

Ref. [23] conducted on-site practical experiments on the effect of airborne dust accumulated on the surface of photovoltaic panels to determine the causes of low efficiency of the photovoltaic system. The researchers also adopted a laboratory solar panels simulation using different PV manufacturing techniques. Deposition of dust causes the voltage generated by the PV panels to decrease. The researchers also noted that the high and very low irradiation result in reducing in the productivity of the PV system. Precipitated dust on the photovoltaic panels is affected in varying proportions according to the technology manufactured from them. The results of the study showed that the photovoltaic panels made with polycrystalline silicon technology coated with an epoxy unit are more affected by the deposited dust than the other tested techniques.

Ref. [24] in his review focused on the great influence of activities conducted by human in exacerbating the issue of desertification in Mesopotamia (Iraq), and how the extension of desertification to millions of hectares caused an increase in the frequency of dust storms in Iraq and neighbouring countries. In this study, a comprehensive and detailed review of all studies concerned with Iraqi dust, whether its characteristics, types, sources, and sediment rates, has been undertaken. Several valuable studies have analysed the physical and chemical properties of dust deposited from different regions of Iraq and the negative impact of this dust on the electrical performance of the PV systems in these areas.

Ref. [25] examined the influence of weather conditions, including the rate of dust deposited on the PV systems. The article showed the great impact of traffic on the productivity of the PV system. The researchers measured the rate of deterioration in the performance of the studied system. Dust and airborne pollutants cause a decrease of at least 12% in the electricity produced from the solar panel if these panels are left without cleaning for a period of two months. As for adopting natural cleaning by rain, the studied panels lost approximately 8% of the electricity generated when comparing their productivity with a clean photovoltaic panel.

Ref. [26] studied the potential of the photovoltaic system and its ability to produce electricity with natural dust accumulation and without the use of manual cleaning. In addition, the article investigated the pros and cons of different cleaning techniques for photovoltaic modules (such as manual cleaning, rain cleaning (natural), automatic and passive cleaning).

The aim of the present investigation is to know the influence of the dust’s physical specifications of deposited dust on photovoltaic systems. The study focused on dust collected from three places in Iraq: Baghdad, Karbala and Hilla. In this study, the following physical properties will be measured: the size of dust particles, their geometrical shape, and the moisture limits of dust, which contains the liquid limit, moisture content, and plastic limit. After collecting the dust and conducting the physical properties experiments on it, the experiments are carried out in a laboratory to show the effect of the dust collected from the three cities on a laboratory solar system and to evaluate the effect of the physical properties of the dust deposited on the electrical performance of the photovoltaic panel.

### 3. Studied region

Iraq is a western Asian country, located in the north-eastern part of the Arabian Peninsula. Iraq does not have wide sea views, as its coastline is around 65 km. Figure 1 indicate Iraq map [27]. Republic of Iraq population in 2018 is about 38.43 million, with an annual population growth rate of around 3.2% [28]. Electricity in Iraq is one of the dilemmas that have lasted for more than 30 years since the US aggression on Iraq in 1991 and the unjust blockade that spanned from 1991 to 2003. The country's power plants have
deteriorated. To this day, the Iraqi citizen in most parts of the country faces an interruption in electricity supplied from the grid for long hours a day [29].

The location of Iraq near the solar belt region makes it receive very high solar radiation intensity suitable for work in many solar applications such as heating air of water, generating electricity with concentrated solar power stations and by photovoltaic cells. Most of Iraq accepts very much higher solar energy from many countries of the world. The average clearing sky in Iraq is about 333 days/year [28]. Iraq suffers from desert areas, which began to creep due to the phenomenon of desertification of agricultural areas, as well as suffer from frequent dust storms especially in spring, summer and autumn [28].

Experimental setup

To know the effect of the physical properties of the dust deposited in the cities of Baghdad, Karbala and Hilla, practical experiments were prepared to measure the physical variables of the dust, and after this step the effect of this dust on the electricity produced from the solar panels is examined. To create typical experimental conditions, the laboratory atmosphere has been adapted as much as possible (maintaining the laboratory temperature at 25°C and RH at 45%). To simulate the effect of solar radiation intensity on the photovoltaic panel productivity, four tungsten lamps were installed each with a capacity of 1600 watts, and in this way a lighting intensity equivalent to 850 W/m² was obtained (equal to the maximum intensity of solar radiation in Iraq during summer season). The sequence of work during the study was as follows: In the first part, the focus was on collecting samples of deposited dust in three locations in the cities of Baghdad, Karbala and Hilla. Within three months, glass sheets (1 m² each) were left in a horizontal position, and the deposited dust was collected periodically every week in small plastic bags. In the second part of the study, the physical specifications of gathered dust were examined. In the last part of the study,
the effect of the accumulation of this dust on the electrical performance of the tested photovoltaic panel was tested.

**Specific gravity of dust Particles**

BS 1377-2: 1990: 9.3 was adopted during the study of physical specification of the three cities collected dust [18]. Equation No. 1 was adopted to measure the density of dust particles, $\rho_s$, and the equation shows that the measured material density is a ratio between the mass of a given volume of examined dust to an equal volume mass of water:

$$\rho_s = \frac{m_s - m_1}{(m_4 - m_1) - (m_3 - m_2)}$$

Where $m_1$ is the masses (in grams) of the gas jar and round plate; $m_2$ is the mass of round plate and soil; $m_3$ is the mass of round plate, soil, and water; and $m_4$ is the mass of round plate and water. To measure the specific density of dust particles, these blocks were measured using a gas container (1 litter) with a rubber cover) with a glass cover, a sensitive scale, a thermometer, in addition to a thermal oven, a temperature of 110 degrees was set.

**Particle shape and surface properties**

The hardness of the dust particles plays an important role in scratching the surface of the PV panel, especially if the dry cleaning is done using a cloth or sponge. Therefore, the measurement of the hardness of these molecules takes on its importance in determining the method of cleaning the dust deposited on the cell. In this study, the moss hardness test was used to determine the engineering of dust particles for the three cities.

**Moisture content, plastic limit, and liquid limit**

Dust types can be divided into four groups: solid, semi-solid, plastic and liquid, depending on the dust content of water. This content of water in dust causes a difference in the properties and engineering behaviour of dust. These categories determine the effect of dust on the area surrounding its sedimentation area, as the dust spreads and expands when it is wet and continues to expand until it reaches a stage where it stops while maintaining a small amount of water. The dust particles’ ability to absorb water, and thus volumetric expansion is greatly affected by the internal components of dust and the proportions of these components. Moisture content is a relationship between the mass of water and the mass of solids (dust particles) in the sample. The plastic limit is the difference between the highest moisture content in the dust to semi-rigid dust. The plasticity index is the difference between the liquid limit and the plastic limit. All samples were subjected to this test. In measurements, a casserole dish, scale with a flat notcher, a glass plate, a scale, a spoon, water, and a drying furnace works at constant temperature of 105°C.

$$w = \frac{M_w}{M_s} \times 100\%$$

Where $w$ is the moisture content, $M_w$ is mass of water and $M_s$ is mass of solids in a dust samples.

**Grain size analysis**

The size of the deposited dust granules is very important in determining the amount of dust that will stick to the surface of the photovoltaic cell. Studies have shown that the smaller the size of dust particles (measured in nanostructures), the greater their adhesion to the surface of the unit and the harder cleaning it. Hence the size of the dust particles gained importance. Standard No. 1999: 13.3-1990: 9.3 was used in
experiments to analyze the size of dust particles by sieves and the humidity scale [31]. In this test, a sieve scale and a hydrometer were used. Table 1 lists the sieve measurements used in this analysis. With the sieve assembly, a vibrator was used to facilitate flipping and distributing the dust across the sieve assembly, in addition to the use of brush. For dust particles that have sizes less than 63 μm (which represent the smallest sieve measurement available in the laboratory), the hydrometer test used to measure these particles. Airborne dust particles, most of which originate from the dry deserts, have sizes less than 63 μm.

Table 1, the used sieves sizes

| Sr. No. | Sieve Size (holes diameter) | Sieve No. |
|---------|-----------------------------|-----------|
| 1       | 3350 μm                     | 6         |
| 2       | 2360 μm                     | 8         |
| 3       | 2000 μm                     | 10        |
| 4       | 600 μm                      | 30        |
| 5       | 425 μm                      | 40        |
| 6       | 300 μm                      | 50        |
| 7       | 212 μm                      | 70        |
| 8       | 150 μm                      | 100       |
| 9       | 75 μm                       | 200       |
| 10      | 63 μm                       | 230       |

When the moisture content in the dust sample is high, the measurements revealed that dust deposits more. It is worth mentioning that during all the part II experiments on the PV panel, its cleaning was done without using water adopting Ref. [25] conclusions and to avoid any PV electrical efficiency losses. In all the tests conducted, alcohol and a surfactant (contains sodium) were employed as detergents. After completing the measurement of the physical dust specifications of the three cities, dust particles were practically distributed homogeneously on the surface of the PV panel in the solar simulator. In this part of the experiments, it will be estimated the effect of the deposition of predetermined quantities of the studied dust particles on the performance of the tested solar panel. The experiments used a photoelectric panel detailed in Table 2. The experiments were conducted at the Solar Energy Laboratory at the Energy and Renewable Energies Technology Center at the University of Technology - Baghdad.

Table 3, the specification of PV module

|                      |                |
|----------------------|----------------|
| Maximum Power (Pmax) | 150 W          |
| Open circuit voltage (Voc) | 21.7 V        |
| Short circuit current (Isc) | 7.46 V        |
| Max. power voltage (Vmp) | 17.3 V        |
| Max. power current (Imp) | 7.26 A        |
| panel Temperature (Tc) | 25ºC           |
| Solar radiation intensity (Gs) | 1000W/m²   |
| Length               | 1.47 m        |
| Width                | 0.62 m        |
| Area                 | 0.9114 m²     |

It is a very difficult issue to uniformly distribute dust on the surface of the PV module. Before starting the experiment (for all experiments) a specific amount of dust is scattered on the surface of the PV panel and to ensure that this dust does not collect in one or several places due to its high moisture content, a vibrator was used to shake and distribute the dust eventually. For this purpose, Jamie Orbit Shaker Oven-80 vibrator is used (this vibrator speed can be adjusted in a range of 10 to 400 rpm). After making sure that the dust has distributed uniformly close to its natural accumulation on the surface of the solar cell as a result of being shaken for several minutes, the simulator lights are on and the measurements of the solar panel performance begins. During experiments the photovoltaic plate is fixed horizontally, dust particles are scattered over the surface of the plate and the vibrators are allowed to distribute them regularly on this surface.
The photovoltaic panel was installed horizontally (the tilt angle is zero degrees) and the components of the deposited dust examined using X-ray diffraction technique (Bruker D8 Advance) and X-ray fluorescence (XRF) (Horiba XGT-7200). Figure 2 shows the results of XRF, while Figure 3 shows the grain size distribution of Baghdad city dust.

Fig. 2, Examination of the components of Baghdad City dust using XRD

Fig. 3, Baghdad City dust particles size distribution

4. Results and Discussion

Physical properties
Tests using the XRD technology for the three cities dust showed that most of the components are similar and contain Al2O3, SiO3, SiO2, MgO, K2O, CaO, Cr2O3, Fe2O3, TiO2, MnO2, NiO, SrO, P2O3, Cl and PM, but they differ in ratios within dust samples for every city. The similarity of the dust components proves that it comes from a single source, and weather and climatic conditions confirm that its source is the Anbar desert, which is adjacent to the three cities from the west. Figure 2 shows the gradation of dust components for Baghdad. In all samples, SiO2 is the largest contributor followed by Calcium Oxide (CaO) and Particle (PM). The difference in the proportions of the components between the three regions depends on the specific circumstances of each city. For example, due to the many and huge construction works, it is found that the calcium carbonate component of some building materials increases in Baghdad [22]. The concentration of power production stations in Baghdad with the Al-Dora refinery, in addition to the heavy traffic, caused an increase in accumulated percentages of PM [32].

The specific density of dust is affected by the density of its components, and this density increases with an increase in the percentage of minerals in the internal composition of the dust. Knowing the minerals components of dust enables to understand the effective part in the studied dust and thus the part that affects the measured specific density. Table 4 shows the specific density of dust for the three cities. The specific density of dust was 2.20, 1.29, and 1.70 for the cities of Baghdad, Karbala, and Hilla, respectively. Baghdad dust has the highest specific density compared to the other two cities. The low specific density of dust in the cities of Karbala and Hilla means that cleaning the photovoltaic panels installed in these cities is naturally easier, that is to say, cleaning with rain showers and wind movement.
The high specific density of Baghdad dust makes the use of natural cleaning harder and the need to use detergents even greater. This results comparable with Ref. [25] conclusions.

Table 5 lists the practical measurements for the plastic and liquid limit of the three cities’ dust. Moisture content describes the amount of water content in the dust, and the amount above it or overflow means that the dust has turned into a plastic limit.

Table 4, the studied cities dusts’ specific densities

| No. | # of gas jar | \(m_1\) | \(m_4\) | \(m_2\) | \(m_3\) | \(\rho_S = (m_2 - m_1) / (m_4 - m_1) - (m_3 - m_2)\) |
|-----|--------------|---------|---------|---------|---------|----------------------------------|
| Baghdad |
| 1   | 545          | 32.022  | 81.16   | 55.122  | 93.943  | 2.21                             |
| 2   | 315          | 18.068  | 41.907  | 27.712  | 48.944  | 2.31                             |
| 3   | 48           | 16.734  | 40.519  | 25.619  | 45.841  | 2.16                             |
| Karbala |
| 1   | 304          | 16.978  | 42.190  | 28.910  | 47.054  | 1.68                             |
| 2   | 48           | 16.534  | 41.059  | 26.395  | 46.077  | 2.03                             |
| 3   | 45           | 16.025  | 40.751  | 26.485  | 44.751  | 1.62                             |
| Hilla |
| 1   | 304          | 16.978  | 42.190  | 19.633  | 42.531  | 1.14                             |
| 2   | 48           | 16.534  | 41.059  | 18.083  | 41.269  | 1.15                             |
| 3   | 45           | 16.025  | 40.751  | 17.437  | 41.270  | 1.58                             |

Table 5, liquid and plastic limit measurements for the three cities dust

| Zone  | Moisture content % | Plasticity index (PI) | Type of plasticity |
|-------|--------------------|-----------------------|--------------------|
| Baghdad | 46%                | 6.31                  | high               |
| Karbala | 18.89%             | 2.711                 | low                |
| Hilla   | 32%                | 4.82                  | moderate           |

The moisture content in Baghdad dust has reached 46%, which means that the adhesion of Baghdad dust to the surface of the photovoltaic plate is high and difficult to clean. The moisture content of Hilla dust was average (32.0%), which means less effort and less cost in cleaning dust off the surface of the PV panel in this city. As for the dust of Karbala, its moisture content was (18.89%), which is considered low, indicating the success of installing PV systems in this city, as it does not require high maintenance and cleaning costs. Equation No. 3 was used to conclude the plasticity index (PI) of tested dust. The results indicate that Baghdad city PI index was (6.31), and this result is high compared to the Karbala dust index (2.711), which is considered low.

Plasticity Index = Liquid Limit - Plastic Limit = LL - PL (3)

The hardness of any material is its resistance to penetration. Therefore, any aggregate has a slight resistance that results from the resistance of the grains, each individually or that is grouped and similar. The degree of hardness of the dust particles is low, which result that the aggregate particles are fine. So, the finer aggregate particles in the dust are less hard. Low-strength dust particles have low impact on PV modules. The hardness measurements result manifests that all the three cities examined dust had a hardness of less than one; which means that the dust of these cities is soft, very delicate, and not hard. Such a description of dust means that its impact will be low when it accumulates on the surfaces of solar panels.

Table 6 lists the physical studied dust specifications for the three cities. The moisture content of Baghdad dust is high, which negatively affects the efficiency of the photovoltaic cells and the need to use expensive cleaning procedures.

For any dust, when the moisture content and plasticity index are high, as in the case of Baghdad city dust, causes greater adhesion of its particles to the surface of the PV modules. This type of dust makes the
process of cleaning the photovoltaic units difficult, and in such a case more water is needed. Since water has become an important and sometimes rare commodity, this type of dust causes high cleaning costs for PV systems. Of the three cities studied, it seems that Karbala is more suitable for installing photovoltaic power stations in terms of the dust, as this city dust has the least impact on the photovoltaic modules. The dust of Karbala has low moisture content, and so is the plasticity index. The results clearly showed that the impact of the Karbala city dust on the performance of the photovoltaic modules is less compared to that of the city of Hilla. On the other hand, the effect of the dust deposited in these two cities on PV performance is less than that of Baghdad dust.

| Zone     | Moisture content (%) | Plasticity index (PI) | Specific gravity (Gs) | Type of plasticity |
|----------|----------------------|-----------------------|-----------------------|-------------------|
| Baghdad  | 46%                  | 6.31                  | 1.1                   | high              |
| Karbala  | 18.89%               | 2.711                 | 1.7                   | low               |
| Hilla    | 32%                  | 4.82                  | 1.29                  | moderate          |

**Electrical properties**

The solar panel performance experiments show a decrease in all electrical parameters (voltage, current, and power) generated due to the deposition of the dust particles of the three cities. Dust was deposited on the surface of the solar panel with specific blocks 50, 100, 150 and 200 grams, and readings were made for the panel’s electrical parameters for each case. Table 7 lists the solar panel output after settling the dust of the three cities on it in fixed weights (100 g and 200 g). When comparing the electric power generated between the two cases of the panel when it is completely clean with the state of deposition of 200 g on it, the power loss was 41.5% for the case of Baghdad dust, 33% when depositing the Karbala dust on the panel, but in the case of Hilla dust, the reduction in the generated power was 35%.

| Zone     | Voltage (V) | Current (A) | Power (W) |
|----------|-------------|-------------|-----------|
|          | 100 g       | 200 g       | 100 g     | 200 g     | 100 g | 200 g |
| No dust  | 20          | 20          | 5.3       | 5.3       | 106   | 106   |
| Baghdad  | 16.1        | 15.3        | 4.44      | 4.05      | 71.48 | 61.965 |
| Hilla    | 17.38       | 16.79       | 4.47      | 4.23      | 77.69 | 71.02 |
| Karbala  | 16.9        | 16.55       | 4.26      | 4.16      | 71.48 | 68.85 |

Falling values of the produced power are high, yet they are consistent with the results of Ref. [23]. Increasing the mass of dust deposited on the photovoltaic modules increases the generated power losses. The experiments results show that any amount of dust accumulating on the PV panel will inevitably cause a decrease in the output of this panel. The highest deterioration in the power generated as a result of dust accumulation was clearly at the accumulation of Baghdad dust, and the lowest degradation was for the case of Karbala city dust. Also, like all previous results in the study, the effect of dust in the city of Hilla was average for the results of the other two cities.

5. **Conclusions**

Photoelectric cells are beginning to get the attention of many countries round the world due to their dependence on free fuel, the sun. Iraq has high solar radiation intensity throughout the year in addition to a clear sky for most of the year. However, the technology of PV systems suffers from obstacles to its use in Iraq, the most important of which is that this country is subject to many dust storms throughout the year. Deposition of suspended dust in the air on the surfaces of solar panels reduces the power generated by these panels. Because of the importance of this topic, and to determine the main causes of this dilemma, the effect of physical dust specifications of gathered dust from three Iraqi cities, Baghdad, Hilla, and Karbala, was studied. With the study of the properties of this dust, the effect of each type on the performance of a photoelectric cell in the laboratory was also studied. The gathered dust samples in the
three cities in its main components is very similar, but the difference in the proportions of these components within each city dust according to its special conditions and the quality of human activities in it. Laboratory measurements showed that the specific density was 2.22, 1.29, and 1.70 for Baghdad, Karbala, and Hillah cities’ dust, respectively. Also, the moisture content was 46%, 18.89% and 32% for dust in the cities of Baghdad, Karbala and Hilla, respectively. As for the total dust plastic, it was high for Baghdad dust, medium for Hilla dust, and low for Karbala dust. The physical properties of the dust deposited on the surface of the photoelectric cell show its clear effect on the performance of the solar panel. This effect varies from city to city. The deposition of Baghdad city dust caused a decrease in the performance of the photovoltaic panel more than that of Karbala and Hilla. The lowest impact on the performance of the photovoltaic panel was for Karbala city dust, which has moisture content, plasticity index, and qualitative density less than that of the other two cities.

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