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The Impact of Soiling on Photovoltaic Performance in Iraq: Review

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Abstract

Solar power systems, also known as photovoltaic (PV) systems, are widely used as a clean and sustainable energy source worldwide. However, these systems can be affected by various factors that contribute to dust accumulation, which have been grouped into five categories: module characteristics, environmental factors, climatic conditions, exposure situations, and soiling properties. Dust accumulation can significantly impact photovoltaic modules' efficiency and power output, leading to a decrease in electricity generation. Airborne dust reduces the intensity of solar radiation by scattering and absorbing it, especially in hot and dry regions such as southern Iraq. This study provides an updated overview of the process of dust accumulation on photovoltaic modules south of Iraq. Moreover, it illustrates the methods used to measure dust accumulation and the performance of solar PV under soiling. Furthermore, it exemplifies the sources of the soiling generation. Additionally, it demonstrates the composition and size of dust particles. Finally, future research perspectives are discussed, and a thorough investigation of the impact of dust is suggested in all regions of Iraq and even in all countries of the world, especially those interested in clean energy. This research aims to understand the effect of dust soiling on PV performance. The outcome of this research will help design the PV module system while considering the most effective method to reduce or prevent dust accumulation in specific areas.

Keywords: Soiling, Dust, PV performance, Solar photovoltaic module.

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1. Introduction

As electricity demand continues to increase, power generation needs to be expanded. However, traditional generation methods contribute significantly to environmental pollution and negatively impact human health due to gas emissions. It is necessary to find a suitable alternative generation method that protects the environment and human health while supporting traditional generation during peak hours [1].

Solar cells offer a promising solution to meet the global energy demand of the future. Solar panels are essential in generating electricity from solar energy, a safe, clean, and abundant source of renewable and sustainable technologies [2]. Many underdeveloped or developing countries still struggle to have a reliable power supply, and using fossil fuels for electricity generation contributes to increased pollution, causing environmental issues [3]. To address this, various solar energy technologies can meet the global energy demand while also helping to mitigate environmental problems and reduce pollution, which leads to the exacerbation of global warming and climate change [4]. If non-renewable energy continues to be used, the average global temperature will rise by about 2 degrees Celsius by 2050 due to emissions [5]. However, maximizing power generation from solar panels requires optimal positioning to capture the most solar radiation. In order for power generation to be maximized at any given moment, PV panels must be in an ideal position to capture most of the solar radiation. PV panels in fixed systems are installed at a specific angle and direction, resulting in a relatively short period of peak solar energy absorption [6].

Additionally, the location is essential, particularly in areas with higher solar radiation levels. For example, the southern region of Iraq is known to receive one of the highest levels of solar radiation or the appropriate level due to high levels of sunlight [7]. The amount of sunlight received varies depending on the location, as shown in Fig. 1, and the figure shows a map displaying the solar power potential in Iraq is employed to evaluate the amount of electricity in kWh that can be generated from 1 kWp. The Iraq region will face more challenges due to weather conditions that can impact PV performance.

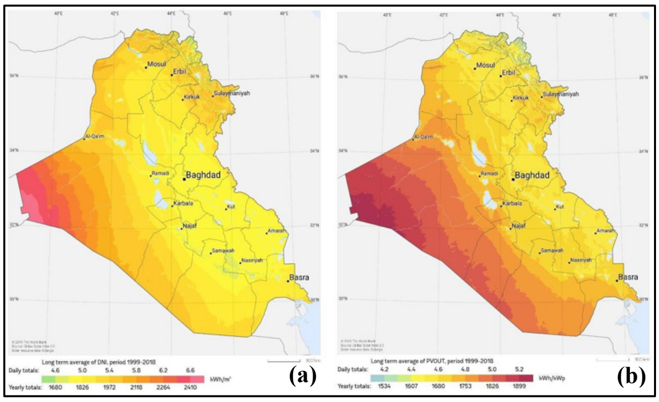

Fig. 1 (a) Direct normal irradiation (b) Photovoltaic power potential in Iraq.

Weather factors should be considered to maximize the power generation of solar panels. Weather factors include wind speed, solar radiation intensity, temperature, relative humidity, and deposition of particles. Deposition of particles, commonly known as pollution, is found in the air or carried by the wind. It is known that pollution is the third factor that determines the efficiency of photovoltaic panels after radiation and temperature; it includes inorganic and organic solid particles such as soil particles, smoke (including factory smoke, vehicle smoke, and wood smoke), bacteria, pollen, fungi, microfibers, and eroded limestone [8].

To mitigate the effects of soiling, researchers widely agree that regular cleaning of PV modules is necessary, typically on a monthly or weekly basis, depending on weather conditions and the amount of airborne dust. Therefore, it is necessary and cannot ignore the importance of conducting a more comprehensive review of the effects of soiling in all geopolitical regions in Iraq to obtain data that can help in taking appropriate action [9].

This article will focus on photovoltaic energy in Iraq and its relationship to weather conditions. The use of photovoltaic technology in Iraq and its potential to harness solar energy will be discussed. In addition, the effect of dust on photovoltaic systems and the challenges it poses to their efficiency will be studied. Finally, an overview of potential solutions to mitigate the dust's adverse effects (by measuring the amount of dust deposited on the modules, measuring the transmittance of light through the modules, or evaluating the actual performance of the modules in response to dust buildup) and enhance the performance of photovoltaic installations in Iraq will be provided.

2. Soiling impact on solar PV in southern Iraq

Basrah, which occupies the southern of Iraq with a total area of 8395.85 km^2, as in Fig. 2. The area is situated between the Latitude (30°55'57"-29°53'56"N) and Longitude (47°59'15"-46°37'55"E). The northern part is located within the Mesopotamian plain, while the southern part is in the southern desert of Iraq. It is bounded in the north by the Euphrates River, in the northwest by Thi-Qar Governorate, in the west by AlSamawa Governorate, in the east by Khur Al Zubair, and in the south by Kuwait. The area has a flat topography, with elevations ranging from a few meters to less than 50 meters above sea level.

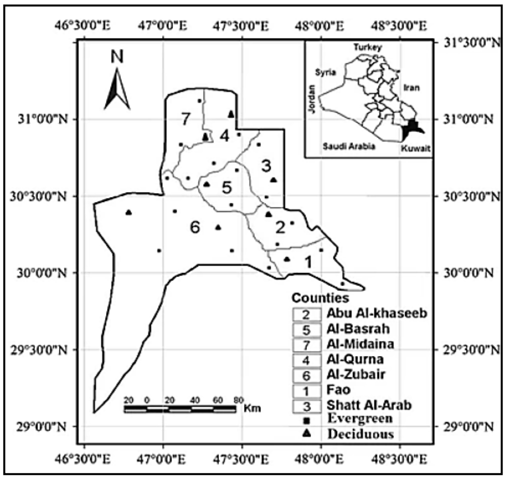

Fig. 2 large part of Basrah Governorate "Reproduced with permission from [11], Environmental Earth Sciences, 2013".

The presence of oil fields characterizes it, and the central marsh in the area is called Hor A-Hammar. The climate in the region is warm to temperate, with a dry and hot summer, especially in the desert. The average humidity from May to October is less than 50%, with low precipitation in most months. Soil erosion and dust storms are joined, and the maximum temperature can exceed 45 °C in summer [10, 11].

2.1. *Soiling generation sources*

Basrah is located in southern Iraq and is recognized as one of the significant sources of dust generation worldwide. As mentioned earlier, the desert region has abundant oil reserves [12]. Currently, desertification is a significant problem in Iraq. The harsh nature, the remoteness, the size of the desert, and another problem is the contamination of oil wells [13]. Regine's atmosphere is mainly impacted by desert dust and gas emissions; sand and dust storms are one of the foremost essential phenomena that have a severe impact on PV performance [14]. The generation of dust particles can be classified as natural or a result of human activities, such as desert storms, industrial emissions, construction debris, vehicle emissions, highway activities, microscopic organisms, pollen, plant material, dander (dead skin cells shed by animals) and other sources, where wind involved in emission, transport and deposition of sand and dust. Local topography, industrial activities, climatic conditions, and agricultural activities significantly generate dust and vary world [15], [8]. Fig. 3 shows the global dust sources are divided into 4 central regions, as shown in the 4 boxes, and are referred to by (1) SAM for all dust sources in South America, (2) SAF for those in South Africa, (3) AUS for those in Australia, and (4) NHE for those in the Northern Hemisphere and shows the extent of the dust that falls across different lands. The most significant quantities of dust come down in the regions of North Africa and the lands to its west, especially in the Great Desert and areas above it. This is natural, given how much sand and soil remains in those places. Heavy dust also reaches the Middle East lands, particularly the Arabian Peninsula, due to sparse plant coverage keeping the earth bare [16].

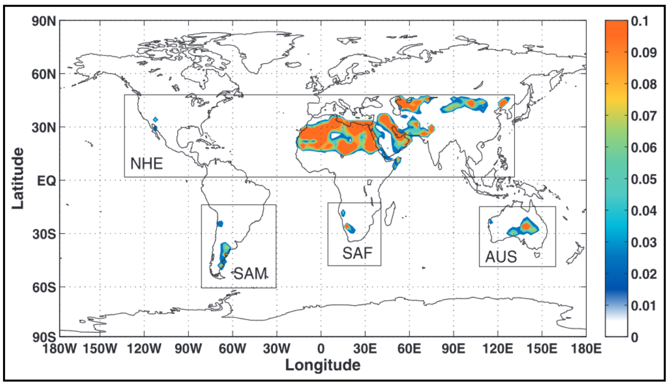

Fig. 3 Global distribution of annual dust emission "Reproduced with permission from [16], Journal of Geophysical Research Atmospheres, 2008".

2.2. *Deposition of dust on PV*

The Iraqi Ministry of Electricity anticipates that by 2030, approximately 15% of the total electricity generated will come from photovoltaic power plants. Solar photovoltaic (PV) systems have the potential to serve as a sustainable alternative to fossil fuels. However, they still face a significant challenge in terms of low efficiency. Theoretical calculations suggest that commercial PV systems could achieve an efficiency of up to 29%, but in reality, the efficiency is limited to a maximum of 26% [17]. Various factors, both internal and external, contribute to the decline in PV panel efficiency, as shown in Fig. 4. The figure shows the various factors that can influence dust accumulation on photovoltaic (PV) systems, all of which can affect the amount of dust that accumulates on the PV surface. The PV constructional factors, on the other hand, involve the PV material, atomic structure, and surface properties, which can impact how dust adheres to the panels. The installation factors, such as orientation and tilt angle, can influence the dust deposition patterns. Finally, the operation and maintenance factors, including cleaning practices and the physical characteristics of the PV system, can affect the ease of dust removal and, consequently, the overall performance of solar energy generation [17].

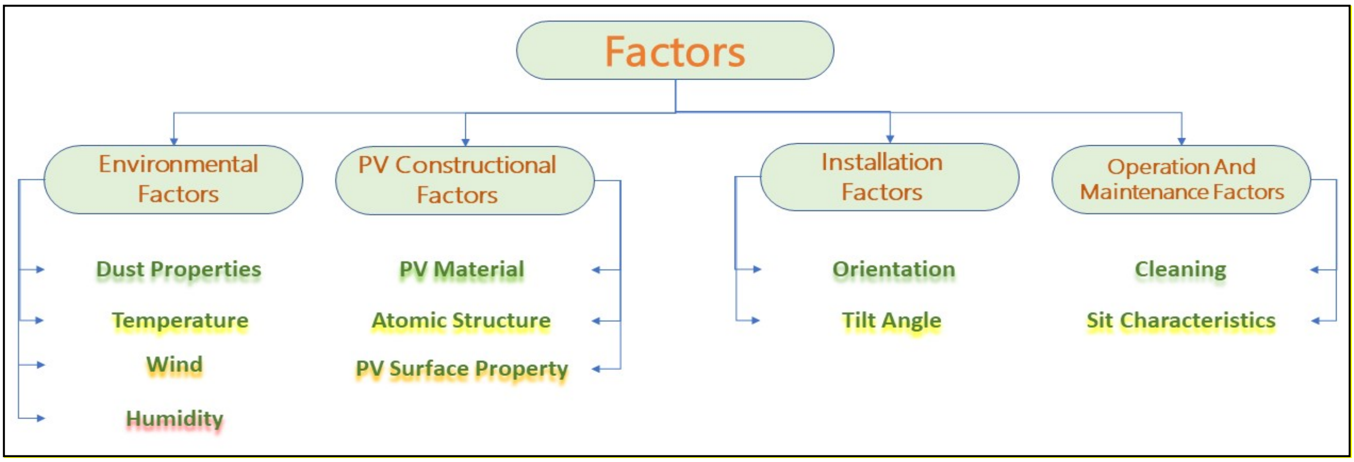

Fig. 4 Factors influencing dust accumulation on a PV.

The efficiency of PV modules decreases when various atmospheric elements, such as debris, water vapor, air molecules, and pollutants, hinder the penetration of sunlight into the panels. Airborne dust particles, more significant than the wavelength of the incoming sunlight, can refract the sunlight, resulting in reduced solar irradiance. Additionally, a thick layer of dust can accumulate on the surface of the PV module. This causes harmful optical disturbance in the transmittance of solar radiation to the photovoltaic solar cell by reflecting, absorbing, and scattering the rays, which leads to a deterioration in the overall performance efficiency. Dust accumulation is influenced by environmental factors such as wind speed, humidity, rainfall, dust sources, particle types, PV module technology, and the surface coverage of PV modules [18].

Numerous studies have been conducted in various countries with abundant solar irradiation and exposure to soiling, such as Morocco, India, Oman, Pakistan, Nigeria, and the United States, to investigate the effects of soiling on solar PV performance [12]. However, experimental data must be used to measure the effect of soiling on PV efficiency in south Iraq. Analyzing the findings from world research will allow for a more comprehensive knowledge of how soiling impacts solar PV systems in Basrah, resulting in the development of viable solutions to reduce the adverse effects of soiling on solar PV performance and improve overall energy generation efficiency.

Rabaia et al. [19], discuss the environmental effects of solar energy systems, which have gained recognition as a renewable energy source. The paper examines different stages of these systems, ranging from design to decommissioning, and explores solutions for waste reduction and minimizing negative impacts. Chanchangi et al. [20], investigated the impact of soiling on photovoltaic modules, explicitly focusing on dust properties and PV surface materials. The results indicate that coal has the most detrimental effect on photovoltaic performance, while salt has the most minor effect. The type of surface material also affects dust accumulation, with acrylic plastic, more dust accumulates than low-iron glass. These results can help select suitable sites for solar farms and guide future studies on dust mitigation technologies.

In a study conducted in East China [21], the impact of dust accumulation and rainfall on the reduction of photovoltaic (PV) power was investigated. The results indicate that the accumulation of dust, mainly consisting of SiO_2 and $CaCO_3$, can cause a 7.4% decrease in PV output power within a week. This emphasizes the importance of implementing effective cleaning strategies to improve the accuracy of PV power output prediction.

Another investigation by Smestad et al. [22], explored the effects of soiling on PV modules by comparing naturally accumulated dirt at seven different locations worldwide. The study revealed that soiling disproportionately impacts the blue and ultraviolet regions of the solar spectrum and can be characterized using a modified version of the Ångström turbidity equation. The distribution of particle sizes adheres to a cleanliness standard and shows a linear correlation with transmittance, allowing estimation of optical consequences of contamination on PV modules.

Alnasser et al. [23], explored the effect of dust, mainly consisting of silicon oxides from building materials, on the performance of PV modules. It reveals that even small amounts of dust accumulation can significantly reduce energy production due to reduced transmittance of solar radiation. The most effective ways to prevent damage from dust buildup include covering the units at night or tilting them downward.

Dida et al. [24], conducted a study on the impact of dust accumulation on the performance of crystalline PV modules in a Saharan environment. The study observed that after 8 weeks of outdoor exposure without cleaning, there was an 8.41% decrease in maximum power output, a 6.10% decrease in short-circuit current, and a 0.51% decrease in open circuit voltage. Furthermore, a sandstorm resulted in a 32% reduction in energy production for a 30 MW PV power plant in the same area. Fan et al. [25], introduced a new approach to quantitatively analyze the influence of dust accumulation on energy efficiency in photovoltaic systems. The method was tested using six different dust types and achieved an accuracy rate of 83.12%. This model offers a straightforward and dependable tool for assessing dust accumulation at specific locations. In a recent study conducted by Salamah et al. [26], examined the impact of dust on the efficiency of solar PV modules in different climatic regions, along with an exploration of various cleaning techniques. The study investigated dust's electrical and optical properties, physical characteristics, and the factors contributing to its accumulation.

2.3. Solar PV performance under soiling

Soiling strongly affects PV performance as it reduces the intensity of sunlight passing toward the solar cells. Much research has measured the effect of soiling on PV efficiency. For example, Tanesab et al. [27] show that the maximum power losses caused by dust varied between 4% and 6% for PV modules in Perth and between 16% and 18% for modules in NTT (Nusa Tenggara Timur). The modules in NTT experienced higher losses due to factors such as their lower tilt angle, longer dry season, and higher relative humidity in the area. These loss results provide valuable information for future PV design in both regions, particularly in NTT, where the losses exceeded the typical dust de-rating factors. It recommended that PV modules installed at lower latitudes and tropical climate areas undergo more frequent cleaning to mitigate these effects.

Valerinoa et al. [28] found that the 10% loss in photovoltaic (PV) energy, which is a conservative estimate, results in an annual cost of 12 million USD for the state of Gujarat. These losses occur due to a combination of human-made particulate matter (PM) and natural dust, which collectively reduce energy production by approximately 5% per gram per square meter of deposited matter. Using a new optical microscopy and image analysis method and a novel theoretical model, it has been demonstrated that over 90% of the deposited mass consists of particles larger than 10 µm in diameter. Despite the dominance of large particles in mass, more than 50% of the adverse effects on PV performance are caused by particles smaller than 5 µm in diameter. This implies that reducing human-made PM emissions in India could significantly enhance PV energy production.

Furthermore, it is recommended to prioritize cleaning methods and explore surface coatings that effectively target the removal of small particles. Concerning natural cleaning, the research indicates that rainfall with an intensity of 8 mm per hour is the threshold for effective cleaning. Halos and Mahdi [14] compared the western parts of Iraq experienced the highest concentration of dust to other areas. This was primarily due to strong winds from the Al Jazeera and western deserts. As a result, cities such as Dhi-Qar, Al-Muthanna, Basrah, and Salahaddin recorded the highest dust concentration values.

At 12 Z, the concentration reached approximately 7700 µg/m^3, while at 9 Z, it was around 7300 µg/m^3, 6800 µg/m^3 at 9 Z, and 6000 µg/m^3 at 6 Z. Zulu time is the same as UTC, the primary time standard by which the world regulates clocks and time. It is the time at the earth's prime meridian, which passes through Greenwich, England. They refer to different time zones, precisely Coordinated Time Zones (UTC). These symbols represent the following:

- 12 Z = 12:00 UTC
- 9 Z = 09:00 UTC
- 6 Z = 06:00 UTC

During the 2018 storm, the dust concentrations decreased at all monitoring stations. Unlike the prolonged 2012 storm, the 2018 storm was relatively short-lived, mainly due to several factors. One of the most significant reasons was the occurrence of gusty winds from sandy desert areas and frequent rainfall. This led to the growth of vegetation cover and, consequently, enhanced soil stability, even in areas that serve as sources of sand and dust.

Sadat et al. [29], investigated the thickness increase of dust accumulated on the PV panel from 0.001 g/cm^2 to 0.033 g/cm^2; several adverse effects on the solar cell performance were observed. The open-circuit voltage experienced a drop of 20.63%, the short-circuit current decreased by 98.02%, and the maximum electrical power output was degraded by 98.13%. Additionally, the conversion efficiency of the solar cell decreased by 98.2%, indicating a significant reduction in overall efficiency. It was found that uniform soiling, where dust accumulates evenly on the PV module, did not significantly impact the fill factor values of the tested solar module. However, previous studies have shown that if dust does not disperse uniformly, the fill factor values can vary considerably.

Through practical experiments conducted during a severe storm, Chaichan et al. [9], found a notable reduction in solar radiation intensity and an increase in ultrafine aerosol particles. Due to dust buildup, indoor and outdoor performance tests also demonstrated decreased current, voltage, power, and electrical efficiency. Cleaning the panels during a storm proved ineffective, but dry-cleaning using bristle brushes after the storm has passed is recommended.

Jendar et al. [30], conducted a study to evaluate power, voltage, and current degradation for solar panels (photovoltaic or PV modules) in northeastern Iraq. The study was based on five months of measurements. The goal was to develop experimental models to predict how temperature and dirt/dust (soiling) impact solar power generation. The key findings were:

- The power loss due to soiling was underestimated.
- There was a daily soiling rate of 0.3% during dust accumulation on the solar panels.

Chaichan et al. [31], studied how sand and dust storms affect the efficiency of solar panels installed in Baghdad. Practical experiments were carried out during a severe dust storm in Baghdad. These experiments showed significant reductions in the intensity of solar radiation and air temperature and an increase in tiny airborne particles compared to regular days. The practical experiments revealed the following:

- Up to a 54.5% reduction in solar radiation intensity.
- A 65.58% decrease in the electrical efficiency of indoor solar panels.
- An 82.93% decrease in electrical efficiency of outdoor solar panels during dust storms in Baghdad.

3. Dust particles size and composition

PV module exposure to outside conditions and dust formation have a deleterious impact on the performance of the technology. Dust is a term used to describe materials that are carried and spread through the air, like tiny particles of soil (which make up most of the dust in the air), smoke from factories, kitchens, cars, and power plants, as well as fog and particles produced by burning fossil fuels, generating electricity, and operating vehicles and machinery. Airborne substances can also include organic matter like bacteria and pollen and inorganic particles from storms, factory emissions, and vapors. Some of these dust particles are small and solid, and they can stay suspended in the air for long periods. They can also be carried long distances away from their source by wind. Dust is a diverse group of particles that vary in size, shape, distribution, and concentration [32]. Dust is a natural occurrence when strong winds suddenly pick up, significantly changing atmospheric pressure during both summer and winter. The amount of dust increases as wind speeds and the temperature. Dust carries the characteristics of the land it passes through or originates from, and its effects are inconsistent. Factors such as humidity, wind speed, and elevation also contribute to dust intensity [8]. Dust particles vary across regions and are affected by local activities. The accumulation of dust, pollutants, and dirt on solar panel surfaces, known as soiling, disrupts the passage of sunlight into PV cells through processes such as dispersion, scattering, and reflection, leading to a decrease in the overall efficiency of the solar photovoltaic system. The concentration of dust particles in the atmosphere depends on climate conditions, local topography, industrial activities, and agricultural practices [33]. The entire process of dust formation and deposition on photovoltage panels, from generation through transmission to adhesion, rebound, and suspension again. Fig. 5 depicts the dust accumulation life cycle and the interrelated factors affecting solar PV systems.

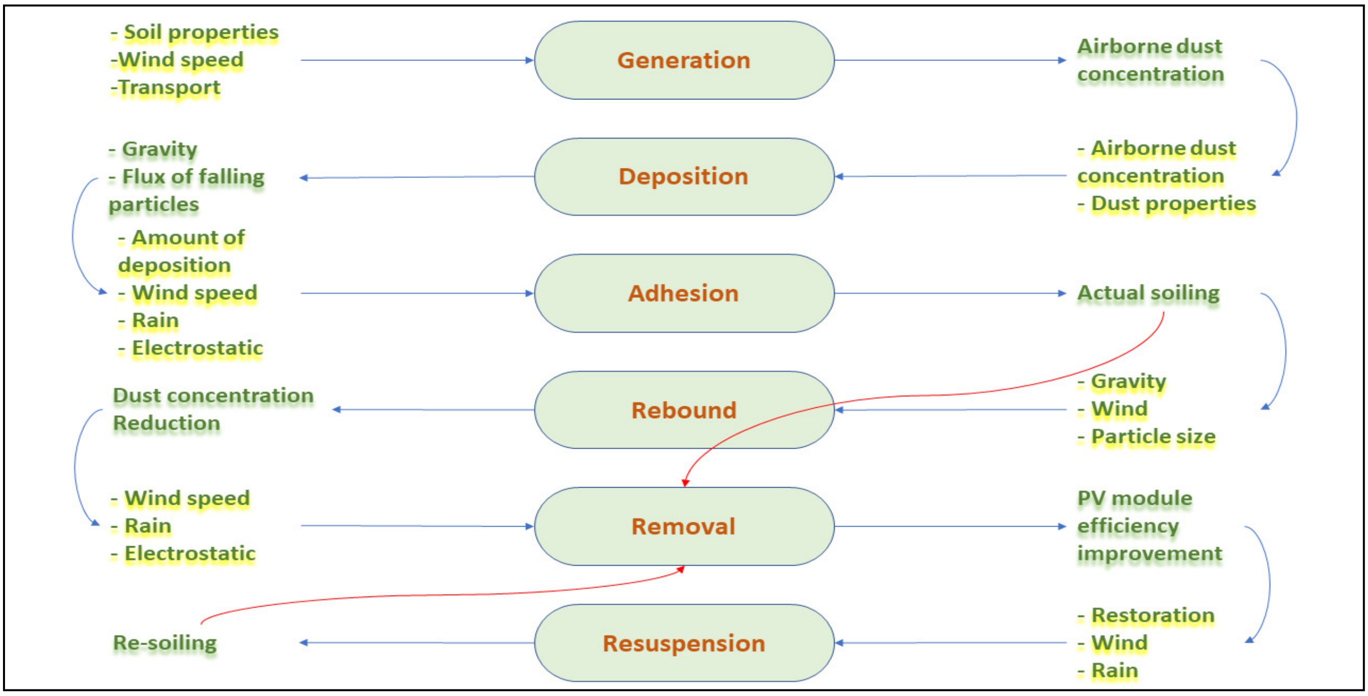

Fig. 5 Dust accumulation life cycle and interrelated factors.

The process begins with generating dust particles, influenced by soil properties, wind speed, and transport processes. These particles can then be deposited on the PV module surfaces through the effects of gravity, the flux of falling particles, and the amount of deposition, which are further influenced by wind speed, rain, and electrostatic forces. The deposited dust particles adhere to the module surfaces, and some may rebound, returning to the suspended state in the air based on factors like gravity, wind, and particle size. Dust particles can also be removed from the module surfaces through natural processes or human interventions, reducing airborne dust concentration. The removed particles may then be resuspended back into the air, influenced by wind, rain, and restoration processes. The diagram also highlights the impact of these dust accumulation processes on the PV module efficiency, with improved efficiency achieved through the reduction of airborne dust concentration and the restoration of the module surfaces [8]. Section two explains all the phases from generation to resuspension phase.

4. User methods for measuring dust accumulation on solar panels

Different ways to measure how much dust accumulates on solar panels include optical transparency tests, comparing reference cells, and advanced analysis techniques like scanning electron microscopy (SEM) and X-Ray Diffraction (XRD). Optical transparency tests are crucial for understanding how dust affects light transmission [34]. Comparing reference cells helps evaluate the decrease in power output due to dust accumulation [35]. SEM and XRD analyses assist in identifying the components of dust, assessing their properties, and developing models to understand the effects of dust on solar panel efficiency [36], [37]. Additionally, some new systems use image processing to measure how much dust is on the panels. They can then predict how much the power output will decrease because of the dust. This provides a new way to monitor dust buildup and its impact on solar panel efficiency [38].

5. Removal of dust from PV

Cleaning should be used to reduce the impact of soiling on photovoltaic energy efficiency. Different methods are used to clean PV systems, some are manual or automatic cleaning, and some are natural cleaning or preventive processes, as shown in Fig. 6. These methods are used to reduce dust accumulation on solar panels and enhance their efficiency. This section of the paper explains these methods.

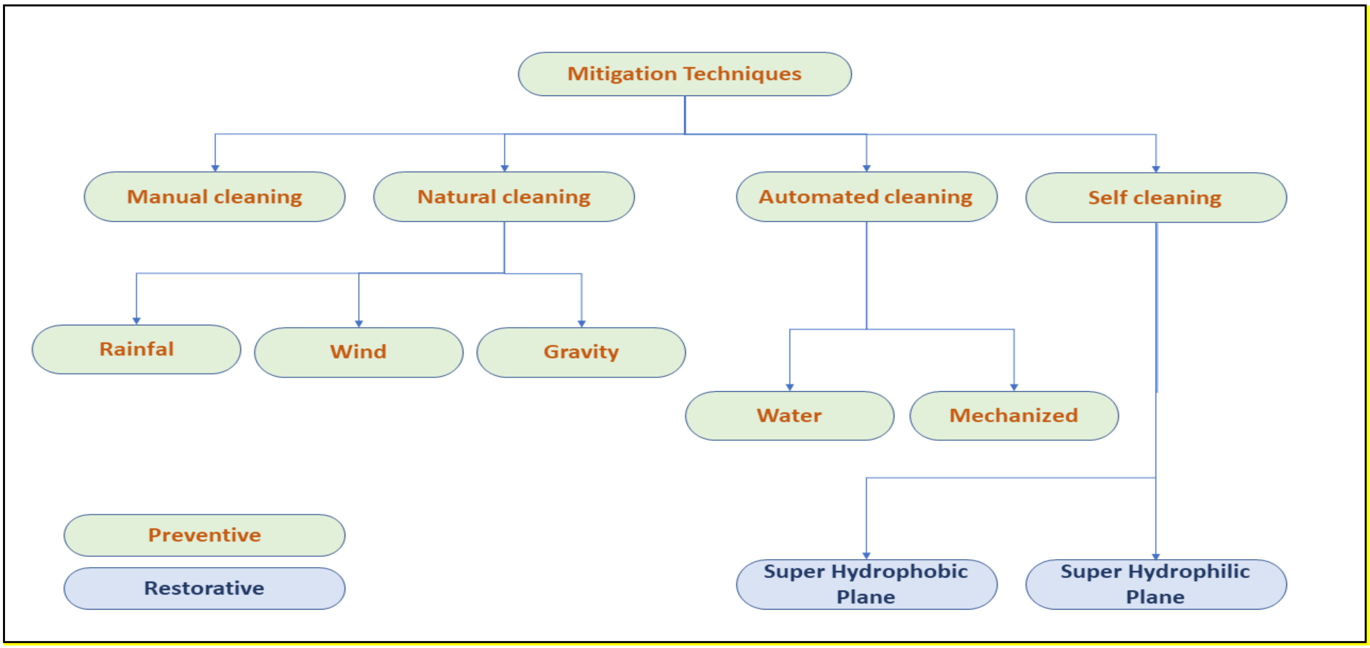

Fig. 6 Mitigation techniques.

5.1. Natural cleaning

Rain, wind, and dew play a role in cleaning solar panels, depending on the weather conditions. Natural cleaning does not require any cost, but it has been reported as ineffective for small dust particles. The efficiency of natural cleaning depends on the amount of rainfall (rain or dew) and the direction of the wind. Rainfall of 3 mm can ensure effective cleaning and restore the solar panels to their initial condition. Anything less than this amount may result in partial cleaning. Precipitation has positive and negative effects depending on the wind speed [39]. High wind speeds during rain enhance the cleaning process by removing dust from the panel through the force of raindrops. The effect may be different in the absence of rain, and depending on the wind's direction, dust may blow onto the surface and lead to its accumulation. When cleaning photovoltaic panels with wind, it was found that larger particles with a diameter greater than 1 micrometer were effectively removed by wind due to the lower suspension velocity required than smaller particles. In the same study, the wind speed that can lead to natural cleaning ranged from 0.82 to 2219.8 m/s. Regarding cleaning with dew, a significant amount of dew was observed on the solar panels, leading to self-cleaning, especially in the early morning [40].

5.2. Manual cleaning

This is a traditional method used for cleaning PV modules, similar to cleaning windows and glass surfaces. One common method for cleaning PV modules involves using brushes and rags to scrub and wash the surface, aiming to restore cleanliness. While this approach effectively removes stubborn dirt and debris, it risks potential abrasion when applied directly to the module surfaces. Moreover, this method is considered costly due to the need for additional cleaning equipment and the labor-intensive nature of the process [8].

5.3. Automated cleaning

This approach utilizes various techniques to clean the surfaces of photovoltaic units, such as mechanical wiping, mechanical cleaning, blowing, vibration, and automated cleaning. The objective of this method is to minimize the need for manual labor by incorporating automation. Islam et al. [41], proved that the use of this technique can increase the output power by 24.40% while minimizing water consumption. It involves using an automatic water recirculation (AWR) method to remove dust from rooftop solar panels in Malaysia. The method includes recycling water and has demonstrated positive results. A new model has also been created to estimate the power output based on the dust accumulation factor. Dahlioui et al. [39], discussed an innovative approach to cleaning photovoltaic panels on dual-axis trackers, which has proven effective in reducing soiling losses and increasing energy production. The automatic cleaning system demonstrates comparable efficiency to manual cleaning and is more cost-effective, particularly in arid regions.

5.4. Self-cleaning

This self-cleaning technology of solar photovoltaic modules uses a chemical or screen layer that repels dust particles using the lotus effect. This helps improve cleanliness and increase efficiency by helping to remove dirt with rainfall. Both hydrophobic surfaces and hydrophilic surfaces enhance the self-cleaning process by facilitating the formation of liquid bridges.

Liquid bridges are a phenomenon where a liquid creates a connection, like a bridge, between two surfaces due to the attraction between the liquid molecules (surface tension). This liquid bridge allows the cleaning liquid to be sprayed onto the solar panel surfaces. The cleaning liquid can then efficiently reach and clean the entire surface of the solar panels, helping to remove dirt and debris and ensuring high cleaning effectiveness. In other words, the liquid bridge helps the cleaning solution spread evenly across the solar panels, enabling thorough cleaning and maintaining the panels' performance [42], [43]. In practical applications of photovoltaic power plants, the surfaces of photovoltaic glass must be highly transparent, smoothness, and hydrophilicity. Excessive dust accumulation on the glass surfaces significantly reduces their transparency, smoothness, and hydrophilia, compromising their self-cleaning capabilities and energy efficiency. To solve this issue, employing hydrophobic or superhydrophobic coatings can improve the self-cleaning capacity and prevent or reduce dust accumulation on glass surfaces. Forming liquid bridges on both hydrophobic and hydrophilic surfaces plays a crucial role in dust deposition. It is closely associated with the dynamic behavior of dust particles on PV glass. Liquid bridges contribute to adhesion and self-cleaning effects between particles and the PV glass surface. Therefore, cleaning technologies for PV glass should consider the effect of liquid bridges in the future [44].

6. Discussion and future research

Based on a review of related research papers, this paper conducted a study to evaluate the impact of soiling on photovoltaic performance in Iraq. Several research gaps were identified, highlighting the sources of soiling in southern Iraq. Dust is one of the most essential parameters affecting PV panel performance, yield, and profitability. However, the characteristics of dust (type, size, shape, meteorology, etc.) vary by location. Further studies are needed to develop accurate insight into the impacts of different air pollutants and dust species on PV efficiency in southern Iraq. It will also help to investigate the potential of solar power generation under future aerosol emission scenarios for optimum solar energy applications.

The review showed that many studies focused on certain influential factors like solar irradiance and dust accumulation. However, several studies demonstrated that other factors significantly contribute to dust accumulation on PV panels and severely impact performance. Many extensively reported dust formations on PV have tremendous effects on technology performance. Few studies examined all these factors simultaneously over scientifically sufficient periods. Factors included weather conditions, design parameters, installation settings, and location characteristics.

Shifting high-polluting power generation to solar system technologies will contribute to air cleaning. In turn, a cleaner atmosphere is expected to be in the interest of the solar PV sector as well as public health, the environment, and the economy. Dust formation is site-specific; most studies presented were not limited to Iraq or focused on Iraqi conditions. Instead, this paper provided generic and location-specific dust impact information to guide further research. Investigating the significant factors influencing PV soiling highlighted above can help understand soiling for a location. This research has reported on mitigation techniques suitable for areas with high solar potential but low adoption; however, the most promising solutions to reduce soiling from solar PV in the future based on the information provided in the reviews adopted in this paper are:

1. Self-cleaning coatings

➢ Implement self-cleaning coatings like super-hydrophobic and super-hydrophilic coatings on photovoltaic modules.

➢ These coatings can reduce dust deposition and enhance the efficiency of the modules.

➢ Utilize super-hydrophobic coatings because they prevent dust accumulation on solar panels, especially in regions with limited rainfall for self-cleaning.

➢ Leverage the self-cleaning properties of these coatings to:

- Inhibit dust adhesion.
- Promote dust separation.
- Prevent dust cementation on the module surfaces.

2. Automated cleaning systems

➢ Automated cleaning techniques, such as mechanical wiping, blowing, vibration, and water recirculation, have shown significant potential.

➢ These systems can increase output power by up to 24.40% while reducing water consumption compared to manual cleaning.

➢ They are more cost-effective, especially in arid regions like Basrah, and demonstrate comparable cleaning efficiency to manual methods.

➢ The automated nature of these systems helps minimize the need for labor-intensive manual cleaning, making them a scalable and efficient solution.

6. Conclusions

This study comprehensively reviewed the impact of soiling on photovoltaic (PV) systems performance in Basrah, southern Iraq. Basrah experiences some of the most challenging environmental conditions for solar deployment, including high irradiation and airborne pollutants. Two key conclusions can be drawn. Firstly, the review confirms that soiling from dust and other pollutants significantly reduces the output of PV modules in Basrah. Dust particles abound in the region due to local geology, agriculture, and industrial activities. Upon accumulation on solar panels, these pollutants decrease sunlight transmission. Secondly, soiling effects are exacerbated by Basrah's unique pollutant profile, which includes dust and toxic substances such as oil waste. While dust-lowering performance is a global PV challenge, Basrah's additional hydrocarbon pollutants pose a distinct problem. If unaddressed, soiling presents a significant threat to the viability and expansion of solar power in Basrah. The literature examined dust particle characteristics in addition to discussing the sources of dust and the mechanics of operations. The factors affecting dust formation were also taken into account. The effects of dust on the photovoltaic module were highlighted, and many related publications were presented. Various mitigation methods are also discussed in detail.

In conclusion, realizing Iraq's solar potential will require strategies tailored to the region. PV technology could deliver on its promise as a renewable solution for the power-hungry city and region. Further research profiling local soiling dynamics will help progress appropriate technological and policy intervention, and it is crucial to have experiment data for measuring the impact of soiling on PV in Basrah.

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