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DUST ACCUMULATION ON PHOTOVOLTAIC MODULES: A REVIEW ON THE EFFECTIVE PARAMETERS

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ABSTRACT

Reviewing the documents regarding the development of photovoltaic systems implies dust accumulation as one of the most significant challenges in arid regions with high solar potential. Moreover, the complexity of this phenomenon and its considerable impacts on the performance of photovoltaic systems, emphasize the need for thorough and comprehensive analysis. Therefore, the current study provided an extensive literature review regarding the parameters affecting dust accumulation. Through the research, the classification of the effective parameters, as well as their impacts on the soiling process on photovoltaic modules' surface, were determined in detail. Furthermore, an in-depth and critical analysis of the state of the art, followed by identification of challenges for future researches, has been presented. The results of the current study can serve as a thorough reference for researchers, designers, and engineers who deal with photovoltaic systems in regions struggling with dust events such as the MENA region and, in particular, Iran.

Keywords: *Dust, photovoltaic, humidity, rain, wind.*

INTRODUCTION

Since 1923, the year in which the first paper published about photovoltaic, up until now, there has been a tremendous scientific afford to increase the applicability of solar photovoltaic systems [1], [2]. Figure 1 shows the trend of all the research activities regarding the photovoltaic systems (1923-2018) [3]. It can be observed that in the recent years due to several factors such as the advances in technology as well as increasing energy demand and environmental concerns, the investigation rate has been sharply increased [4]–[11]. Reviewing the related literature shows that before 2008, very limited and scattered works have been conducted regarding the soiling impacts on the performance and efficiency of photovoltaic panels [12]. However, with the development of photovoltaic systems in the world, especially in areas such as the MENA region, which despite the high potential of radiation, are struggling to deal with the dust challenges, the dust problem becomes more apparent. Therefore, a significant increase in the number of researches published in this area, especially since 2009, can be observed. For example, out of a total of 590 studies in this area, 559 studies have been published in the past decade (Figure 2) [3].

In one of the early studies in this area, Selim et al. experimentally studied long-term soiling effects on the electrical production of a solar farm near Riyadh, Saudi Arabia [13]. The photovoltaic panels were tilted 24.6°, and the monthly electrical generations for dusty and daily-cleaned panels were compared. The reduction in electricity production at the end of the eighth month was 32%. Unfortunately, there has been no report on the dust level and the physical characteristics of the site. Therefore, the provided data might be misleading. For instance, in a dusty environment, such a reduction in the output may occur in a few weeks, not in eight months. In another work carried out in Egypt by Hassan et al. [14], it was shown that a decrease in the output in the first exposure month is faster. They specified that the drop in the electrical output increased from 33.5% after 30 days to 65.8% after 180 days without cleaning.

Furthermore, El-Shobokshy and Hussein [5] showed that the dust particle properties, including chemical compositions, particle size, and its density on the surface, have a great influence on the output energy of solar panels. However, they did not take wind impacts into account in their indoor experiments. While in normal conditions, gentle winds have substantial influences on the level of dust settlement on flat plates [15], [16].

Moreover, few works have been done to investigate the effect of dust accumulation in regions with high precipitation. Hottel and Woertz [17], in a three-month period, showed that the soiling effects are surprisingly small (4.7%) on the overall performance of 30° tilted collectors. They suggested that the self-cleaning properties of glass

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due to the high precipitation in Boston, USA. In another similar study, Dietz [18] reported a 5% decrease in the transmission coefficient due to dust accumulation. These findings were later confirmed by Michalsky et al. [19], during a two-month test, in Albany, New York. During this period, it was rainy at least once in every ten days. The results of their experiments showed a 1% decrease due to dust accumulation.

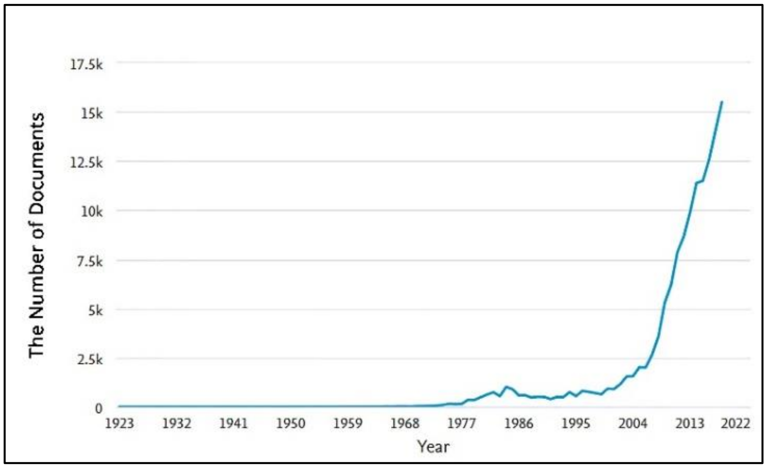

Figure 1. The world trend of studies regarding photovoltaic systems (1923-2018) [3].

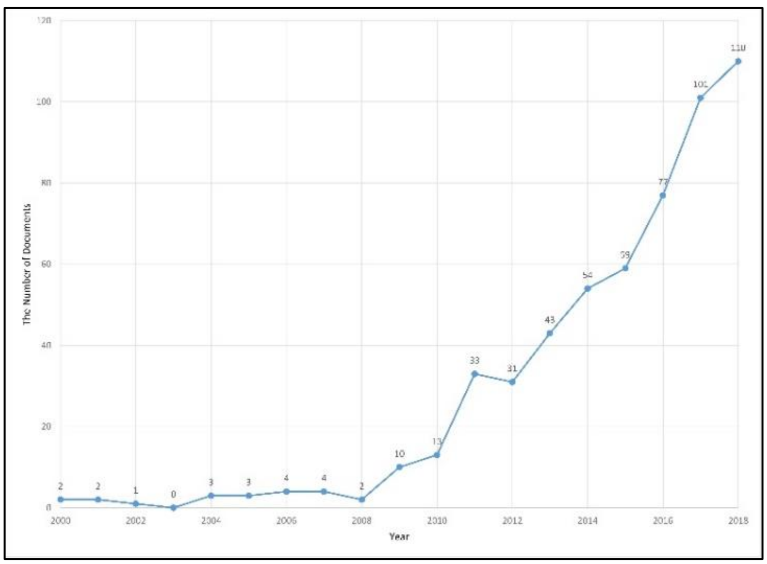

Figure 2. The world trend of studies regarding soiling impacts on photovoltaic systems (2000-2018) [3].

A review of the related studies suggests that limited preliminary researches in this area did not provide sufficient data on the soiling rate and the atmospheric conditions in the test sites. Furthermore, it can be understood that several factors, such as environmental parameters, could strongly affect the settlement of dust on the modules and their output performances. Consequently, further detailed information will be needed to design and optimize photovoltaic solar systems, as well as to estimate the drop in their output because of dust accumulation for different regions. Therefore, the present study was conducted to review the chief related researches regarding the soiling on photovoltaic panels and categorized the parameters affecting this process. Moreover, a critical evaluation of the state of the art, followed by determining the remaining challenges for future researches, has been provided. The results of the current study can serve as a thorough reference for researchers, designers, and engineers who deal with photovoltaic systems in regions struggling with dust events such as the MENA region.

PARAMETERS AFFECTING DUST ACCUMULATION

In the following section, the main parameters affecting the accumulation of dust particles on the surface of photovoltaic panels are categorized, and some of the related articles are reviewed.

The properties of dust particles

The characteristics of dust particles, including particle size, dispersion, and distribution morphology, as well as the dust chemical composition, have a significant influence on the dust accumulation process [20]. Different origins of the accumulated dust result in various chemical and physical properties. In a comprehensive and thorough recent study, Gholami et al. [21] investigated the multiple sources of dust activities as well as their frequencies in the MENA region. Reviewing the literature shows that in order to determine and analyzed some of these properties, several optical techniques such as scanning electron microscopy and scanning probe microscopy have been used [22].

P. Piedra and H. Moosmüller showed the main two properties of dust particles affect losses are its size and absorptivity. Their study revealed that fine particles scatter back more radiation than coarse ones. Likewise, particles whose ratio of particle length to penetration depth is about 1 tend to absorb more radiation than others [23]. In this regard, several studies have been done to investigate the properties of dust particles in different regions.

In a study conducted in Kuwait [24], Qasem et al. reported that the grain size of the accumulated dust particles was between 4 to 8µm. Furthermore, the main components of dust were quartz, followed by calcite and albite. It should be mentioned that the dust chemical composition and size particles are varied from location to location. For instance, the range of dust particle size was reported to be 0.5−176µm in Dhahran, KSA [25], 2–10µm in KU Leuven, Belgium [26], [27], 95−780µm in Algeria [28], 53−75µm in Bangkok, Thailand [29], 0.5−1000µm in Libya (Sahara desert) [30], [31], 2−63µm in Oman [32] and an average of 2µm in Qatar [33]. Furthermore, it was mentioned that although the shape of the dust particles was irregular, they could approximately consider being spherical [22].

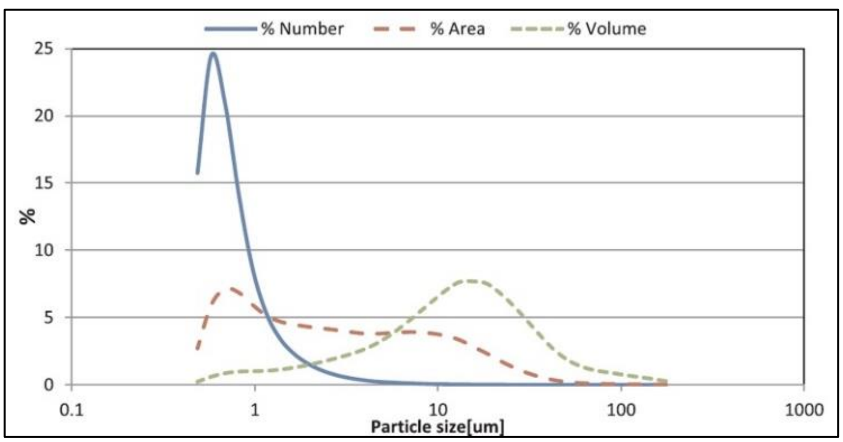

Figure 3. The fractions of the number, area, and volume of the accumulated dust particles distribution according to the study done by El-Shobokshy et al. [34].

Analyzing the related literature implies that the accumulation of finer dust particles has a more significant impact on the performance of photovoltaic panels than that of coarser particles. According to a thorough study conducted by El-Shobokshy et al. [34], the distribution frequency, covered area, and occupied volume of dust particles are investigated according to their particle sizes (Figure 3).

Besides the particle size, its dispersion and distribution morphology, the chemical composition of dust plays an important role in the dust adhesion between the particles as well as to the surface. In this regard, several studies have been done to investigate the major chemical component of accumulated dust particles and their impact on the performance of PV panels [35].

Figure 4 illustrates the results of the XRF analysis done by Elminir et al. [36]. Based on their study, the main components were silicon from desert sand (quartz, or silicon dioxide, $SiO2$), calcium from the mineral calcite (calcium carbonate, $CaCO3$). Moreover, the other components, such as Na, Zn, Al, Fe, Mg, K, and S, were also found. In a similar study done by Said and Walwil [25], as can be observed in Figure 5, oxygen (O) was introduced as the highest chemical concentration followed by Ca, Si, S, and Fe. In a recent study, Gholami et al. [37] reported the average mass fraction of each dust component during an experimental examination in Tehran, Iran (Figure 6).

Reviewing the literature confirms that the chemical composition of dust varies from site to site. For instance, in an early study [38], Modaihsh reported that the main minerals of dust in Riyadh, KSA were quartz, calcite, and heavy metals (such as Pb, Zn, Cd, Ni, and Co). While in a thorough study done by Javed et al. [39], it was reported that the main minerals of dust in Doha, Qatar, were dolomite, calcite, quartz, and gypsum. Furthermore, the chemical composition of dust particles and their color, have a great impact on the degree of reduction in the transmittance coefficient of the glass and the output losses of PV panels [22]. Therefore, an on-site study would be necessary for detailed information in different locations.

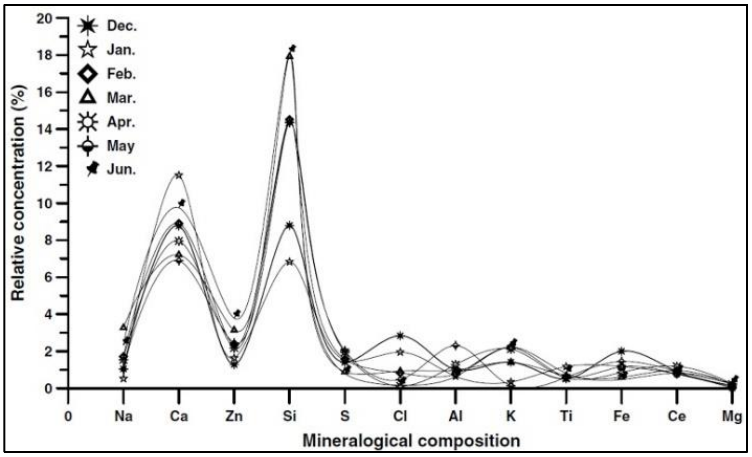

Figure 4. XRF analysis of the accumulated dust according to the study done by Elminir et al. [36].

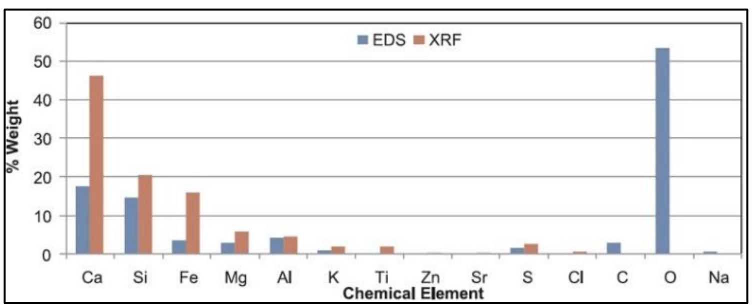

Figure 5. XRF and EDS analysis of the accumulated dust according to the study done by Said and Walwil [25].

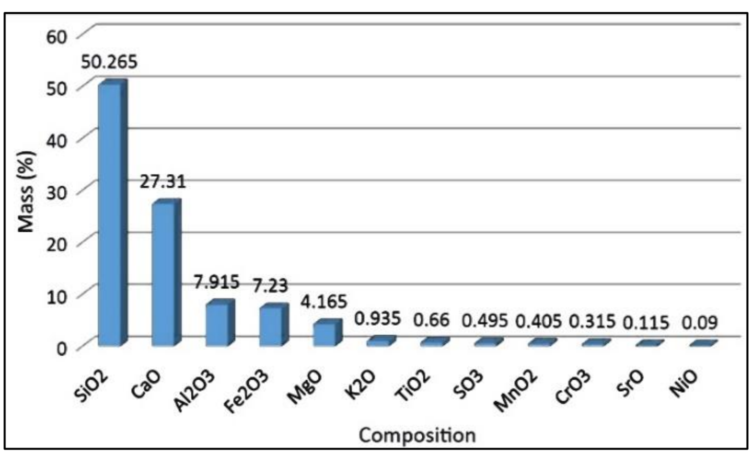

Figure 6. Average mass fraction of each dust component in Tehran, Iran, reported by Gholami et al. [37].

Humidity and the adhesion force

Moisture is one of the effective parameters increasing the accumulation of dust particles on the surface of photovoltaic panels. In general, as the absolute humidity on a site increases, the amount of dust accumulation rises [40]. This is due to the fact that as the moisture condensates on the surface of photovoltaic panels, it creates capillary bridges in the gap between the dust particles and the surface. This creates a capillary force, which subsequently increases the adhesion between the dust particles and the surface of the panels and therefore accelerates the dust deposition rate [41]–[43]. Mekhilef et al. [44], stated that the adhesion force between the dust particles and the surface is greatly influenced by the amount of atmospheric moisture. They reported that as the relative humidity decreases, the efficiency increases, which is due to the reduction of soiling. Reviewing the related literature demonstrates that several models, such as the JRK model, the Rabinovich model, and the Derjaguin, Muller, and Toporov (DMT) model, have been used to measure the adhesion force between the dust particles and the surfaces [22], [45], [46].

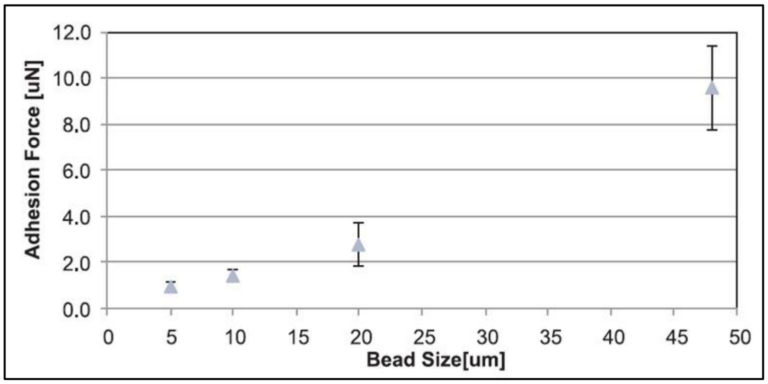

Figure 7. The relation between the size of dust particles and the adhesion force reported by Said and Walwil [25].

Besides the humidity, it should be noted that the adhesion force depends on the chemical composition and the size of the dust particles as well. Figure 7 illustrates the adhesion force variation versus the size of dust particles according to the work done by Said et al. [25]. This study confirms the previous results reported by Corn [47]. Furthermore, as expressed in the work done by Penney [48], the contact surface between dust particles and the surface of panels has a significant impact on the adhesion force between the particles and the surface.

As can be observed in Figure 7 and stated by the work done by Somasundaran et al. [49], the order of magnitude of the adhesion force between the surface and the dust particles is μN. By investigating the morphology of the accumulated dust as well as its chemical mechanisms, Kazmerski et al. [50], [51], reported that the adhesion force between the dust particles themselves is greater than the adhesion force between the glass surface and the particles. However, Hassan et al. [52], revealed that for the dried-out mud on the surface of photovoltaic panels, the adhesion force between the dust particles and the surface is significantly larger than the adhesion force between the particles.

In general, in the presence of moisture in the air, dust particles absorb some of the water vapor and form a muddy layer on the surface of the panels. As the layer dried under the sunlight radiation, it creates a cement-like mixture, which is much more difficult to remove from the surface [52], [53]. This demonstrates the salient influence of humidity on the accumulation of dust particles on the surface of photovoltaic panels [54]–[56].

The cover glass of the panel

Besides the dust properties, the physical and chemical characteristics of the cover glass surface have great impacts on the accumulation rate of dust and the adhesion force between the particles and the surface [57]–[59]. The studies in this regard are mainly focused to investigate the effects of applying different nanocoatings on the glass cover of panels. For instance, in a study in Minnesota, USA, Brown et al. [60], compared the reported that after a 4-months period, the transmission coefficient loss for the coated and uncoated surfaces were respectively 20% and 25%.

In a thorough investigation of the adhesion of dust particles to the surface of photovoltaic panels at the microscale, Kazmerski et al. [51], showed that by applying hydrophilic and hydrophobic coatings on the surface, the adhesion force between the dust particles and the surface reduced from 90nN to 12nN. In a recent study, Gholami et al. [61], compared and analyzed the effect of both hydrophilic and hydrophobic coatings for three different film thicknesses of 30nm, 50nm, and 70nm. It was shown that, by applying nanocoatings on the cover glass surface, dust accumulation rate reduces significantly. Their results indicated an average reduction of transmission coefficient loss from 22% to 0.5% over a test period of 70 days.

These studies emphasize the significant effects of the cover glass of the panel on the accumulation process. Although recently several studies have been done in this field, further detailed and comprehensive researches will be needed to help to solve dust accumulation problems, particularly in arid regions.

Rain

In general, rain is considered as one of the natural methods of swiping dust particles away from the surface of the photovoltaic panels [62]. Reviewing the related studies that have been recently carried out, shows that the rotation of solar panels to a vertical position during the night and rainy days could be a practical method to wash dust particles away from the panels [63], [64]. However, it is difficult to rotate large arrays of solar panels, and it consumes a noticeable amount of energy as well as increases the maintenance cost [61].

Reviewing the literature shows that in the regions with a little rainfall, such as MENA, the amount of dust accumulation on the panels is very high. This results in a dramatic reduction of PV output [65]–[67]. For example, in Dhahran, Saudi Arabia, after six months of exposure to environmental conditions without cleaning, a 50% drop in the electrical generation of the panels has been reported [35]. In another study, in Arar, Saudi Arabia, a daily reduction of 2.78% for the short circuit current was recorded [68]. In Egypt, Hegazy reported a 20% drop in the transmission coefficient of the glass cover after a month of exposure to environmental conditions. This drop led to a 70% decrease in the electrical generation of the photovoltaic system [69].

In a detailed research study in Isfahan, Gholami et al. [70], experimentally studied parameters influencing the accumulation of dust particles. They reported that over a 70-day test period without any rain, the transmission coefficient of the glass will drop by up to 25%. Furthermore, they suggested a universal correlation between the amount of dust surface density and the loss of transmission coefficient (Figure 8). This correlation was later tested and verified by another experimental study in Tehran [37].

Furthermore, Gholami et al. [61] investigated the self-cleaning properties of supper hydrophobic and supper hydrophilic nanocoatings as a dust removal solution. During their experiments, they also investigate the cleaning effect of rain on different surface nanocoatings. It was shown that although rain would remove some of the dust particles from the surface, in low precipitation, it creates some stain on the panel surface. These stains themselves lead to a noticeable reduction in the transmission coefficient of the cover glass. Although, this effect could be minimized by the coating of hydrophobic or hydrophilic nanofilms on the cover glass surface.

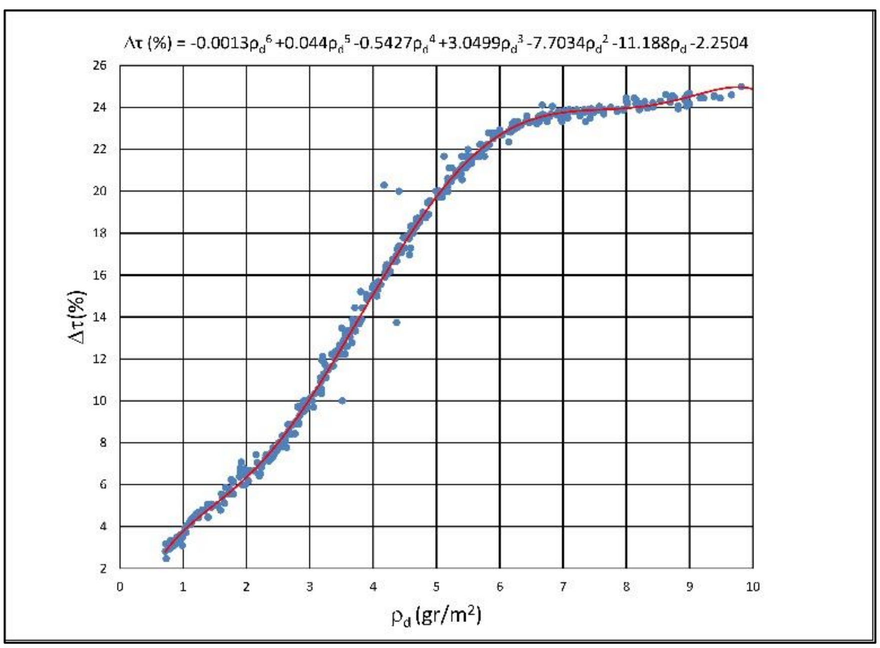

Figure 8. The drop in the transmission coefficient due to soiling, reported by Gholami et al. [70].

Wind

Depending on its direction and velocity, wind can have different impacts on the soiling process on the panels. On the one hand, wind can blow away the settled dust particles, resulting in a reduction of dust concentration [71]. On the other hand, wind could lift dust particles from the deserted areas and move them to a site and increase the dust level in the site [72]. For instance, in the Libyan desert, O'Hara et al. [30] reported an increase in dust concentration levels on the surface due to a rise in the monthly average of wind speed. According to Gholami et al. [70], light wind swept away some of the dust particles, for the surfaces facing the wind. However, because of vortex creation on the surface of the panels, dust particles were accumulated with a higher rate on the panels facing away from the wind. Their results stated that both the orientation of panels and the dominant wind direction have significant impacts on dust accumulation process.

To simulate the effects of wind velocity as well as its direction on the dust surface density on PV panels, Goossens et al. [73], conducted several field tests and measurements in a wind tunnel. Their results showed that the direction of the wind has a more significant impact on dust accumulation process than the wind speed. Furthermore, they stated that wind speed more than $2.59 m.s^{-1}$ results in an increase in soiling and a sharp decline in the output performance of the panels. While as they reported, at lower wind speeds, dust accumulation rate is reduced. In this regard, Callot [71] stated that the minimum threshold of wind speed for the accumulation of dust in Libya is $6.5 m.s^{-1}$. In another study on Mars, Gaier et al. [64] revealed that the effect of particle size on the accumulation process varies with wind speed. They stated that in high wind speed (89 to $116 m.s^{-1}$), there is not any significant difference between the performance loss caused by large particles (larger than 75μm) and small particles (30μm). These results were later confirmed by AlBusairi et al. [74]. According to their findings, dust accumulation could be neglected at wind speed higher than $24 m.s^{-1}$.

Reviewing the literature shows that the wind impacts on the soiling process varies from site to site and depends on its direction and speed. Therefore, site study would be necessary for detailed information before installing large scale power plants.

Gravity

Gravity is considered as one of the natural dust removal methods from the surfaces. Gholami et al. [70] showed that for both coated and uncoated surfaces, increasing the tilt angle increases the gravity impacts on dust particles and leads to a reduction in the amount of settled dust (Figure 9). However, due to the decrease in the amount of adhesion force, for the coated samples, the gravity force has more impact. Furthermore, they stated that the variation of the mounting angle changes the amount of radiation received by the panel and may have a substantial impact on the performance of solar panels. Hence, it is essential to find the optimum mounting angle on a site.

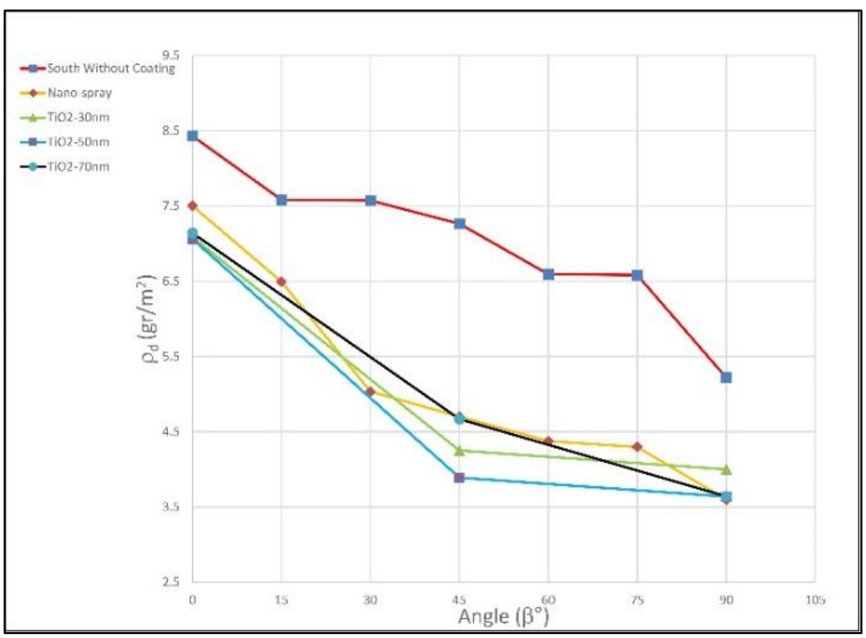

Figure 9. Dust surface density variation due to the change in the tilt angle [70].

To determine the optimum mounting angle in Kerman, Iran, an experimental study was conducted by Rouholamini et al. [75]. Comparing theoretical models and the measured data, confirmed that due to dust accumulation, the computational models do not have the accuracy in predicting the optimum angle. Therefore, they suggested that to determine the optimum mounting angle on a site, the environmental factors such as dust accumulation, have to be taken in to account. Following this result, Talebizadeh et al. [76], experimentally measured the optimum annual fixed tilt angle of the panels in Kerman. It was shown that considering dust effects, the optimum mounting angle in Kerman is 10° higher than the theoretically predicted angle (30°). They reported that in such an angle (40°), the power output of the system increased by an average of 3%.

Recently, considering the gravitational force, several studies have been conducted to investigate the utilization of bifacial vertical modules in order to minimize dust effects [77]–[79]. These studies show that sometimes in a dusty environment, vertical mounting of bifacial modules could be a better solution to overcome the dust accumulation problem.

RESULTS AND DISCUSSION

Reviewing the related literature implies an increasing tendency toward both research and development of PV systems in the world. However, despite great favorable solar conditions within the arid regions, dust activities in these areas have created considerable challenges and obstacles in the development of PV systems.

Therefore, in the current paper, some of the chief documents regarding parameters affecting dust accumulation on the photovoltaic systems have been reviewed. These parameters could be classified into four main categories, including dust particle properties, the glass cover characteristics, the adhesion force between dust and the surface, and finally, the environmental conditions. The latter category consists of several subcategories, such as rain, wind, and gravity. It should be noted that each of these parameters could influence others.

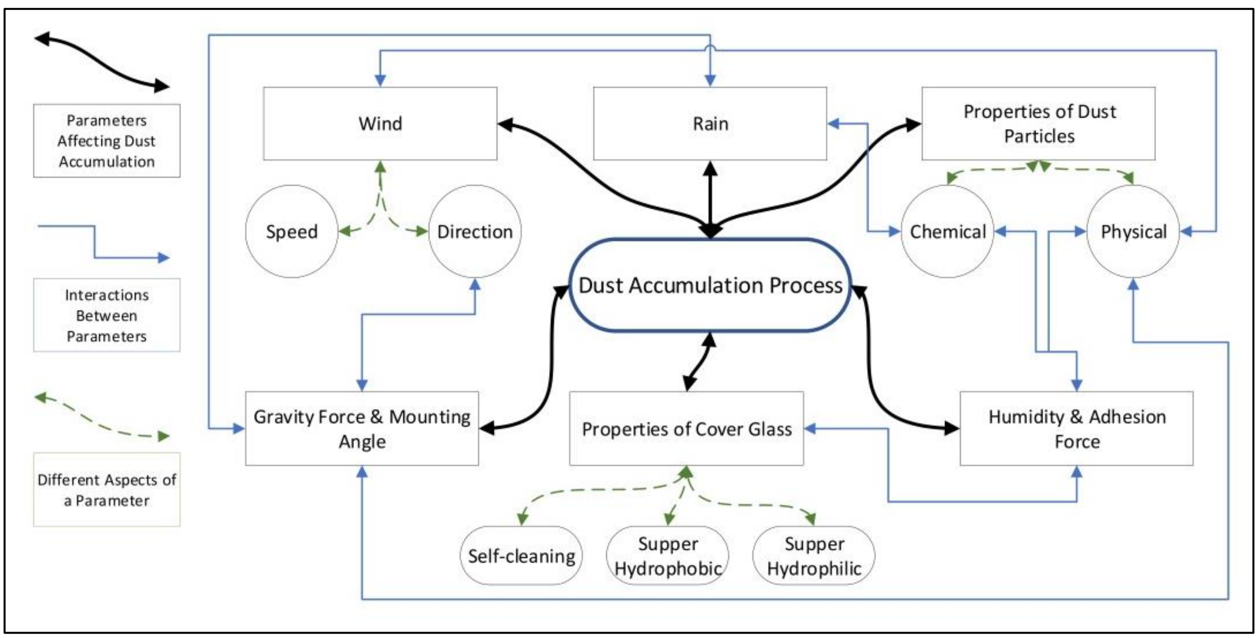

Figure 10. Parameters affecting the soiling process and their interactions and effects on each other.

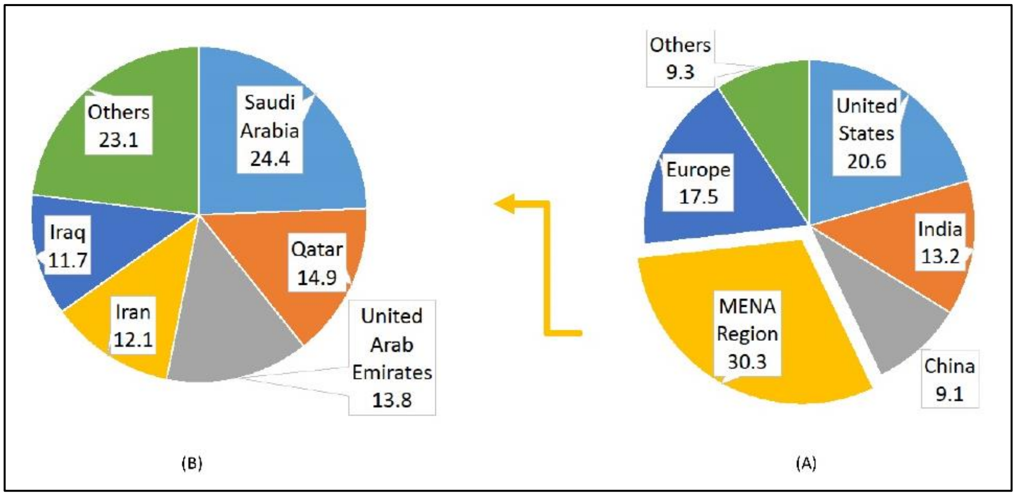

Figure 11. Regional summary of Studies regarding dust impacts on photovoltaic systems [3].

Reviewing the literature, all the various parameters affecting the soiling process and their impacts on each other were classified and introduced. Figure 10 illustrated the parameters affecting the soiling process as well as their interactions and effects on each other.

Furthermore, it was shown that some of these parameters vary from site to site, leading to various impacts on the dust accumulation process. Therefore, an on-site study would be necessary for detailed information in different locations. Figure 11 illustrates a regional summary of research studies regarding dust impacts on photovoltaic systems. As can be seen in Figure 11.A, the MENA region, which struggles the most with dust challenges, accounts for the highest share of the documents (30.3%). In this regard, Saudi Arabia (24.4%), Qatar (14.9%), UAE (13.8%), Iran (12.1%), and Iraq (11.7%) are the countries with the highest research studies in MENA region (Figure 11.B).

Furthermore, A critical evaluation of the reviewed documents in the current paper revealed the remaining challenges in this field, which are highly recommended to be investigated to provide better utilization of PV systems in the future.

CONCLUSION

The environmental concerns, as well as energy demand, increases the number of studies regarding solar energy harnessing as well as its challenges. In this regard, arid regions, such as North Africa and the Middle East, are known as the regions with high solar potential. However, these regions severely struggle with dust activities. Frequent Dust storms in these regions are considered as prominent obstacles in the development path of PV systems.

In order to overcome the dust accumulation problem and introduce effective cleaning methods, several studies have been done to determine parameters affecting the deposition process. In the current paper, the main conducted studies regarding these parameters were reviewed, summarized, and categorized to serve as a guide for any designers, engineers, and researchers working in the PV field. Although recent studies have successfully identified the main parameters affecting dust accumulation on the surface of PV panels, several challenges should still be overcome to achieve a better utilization for the PV systems. The challenges and shortages in this regard are listed as follows:

1) Lack of large-scale analysis considering dust effects is apparent, and most of the reviewed works were done on a small scale with limited PV panels.

2) Due to the variety of environmental conditions and their impacts on soiling, a few general correlation forms (such as the one reported by Gholami et al. [67]) are presented in the literature, and there is a noticeable gap regarding the modeling of dust accumulation and its impacts.

3) The necessity of various cleaning methods to overcome dust accumulation problems was concluded by most of the studied papers. However, the lack of cleaning strategies and related studies, especially in Iranian scientific works, is obvious.

4) Bird droppings on PV systems could be as severe as dust problems, and if neglected, it could cause hot spot and module failure. Therefore, due to the sharp development of PV installation around the world, bird droppings will be more problematic in the future, and further studies should be conducted in this regard.

Further researches regarding these challenges and shortages are suggested for future studies. The results of the current study can serve as a thorough reference for researchers, designers, and engineers who deal with photovoltaic systems in regions struggling with dust events such as the MENA region.

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