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Review

A Comprehensive Review of a Decade of Field PV Soiling Assessment in QEERI's Outdoor Test Facility in Qatar: Learned Lessons and Recommendations

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Abstract: Soiling of photovoltaic (PV) modules is a major issue due to its critical impact on PV performance and reliability, especially in the desert and arid regions such as the state of Qatar. Soiling frequently results in a severe reduction in PV power generation, which drastically affects the economical profitability of the PV plant, and therefore, must be mitigated. The most common way of mitigating PV soiling is surface cleaning. However, the latter could consequently increase the associated operation and maintenance (O&M) cost of the PV site. However, previous studies indicated that even if the best-optimized cleaning schemes are used, the actual global solar-power production can still be reduced by about 4%, which is associated with at least EUR 5 billion in annual revenue losses worldwide. This loss is expected to reach a conservative value of EUR 7 billion in 2023. Accordingly, investigating the interplayed physics phenomena related to the various soiling processes, the site-specific O&M costs, along with a techno-economical assessment of state-of-the-art soiling mitigation strategies (including innovative anti-soiling coating materials) is of paramount importance. The goal of this comprehensive report is to provide the solar community at large, and those focusing on the desert environment in particular, with real field measurements that provide key findings and challenges in addressing soiling research obtained from multiyear testing at the Outdoor Test Facility (OTF) field station, located in the desert environment of the city of Doha, in the state of Qatar.

Keywords: soiling; solar energy; outdoor conditions; mitigation; cleaning

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1. Introduction

The term "soiling" may invoke different meanings. In the aerosol field, it is commonly attributed to the number of particles present on a given surface (e.g., surface density, which reflects the number or, in particular scenarios, the mass of dust particles per surface), while in the PV industry, it is mainly correlated with optical fixtures due to soiling accumulated on the front glass of PV module (e.g., light transmission, absorption, and reflection losses) as the absorbed light governs the associated PV module power directly. The focus here is to highlight the impact of the soiling on the PV energy yield generated in real-world conditions, such as outdoor test facilities (OTFs), such as the one located in Doha (Qatar). Subsequently, this impact might be discussed and compared with that observed in other geographical locations.

Recently, the topic of PV soiling has recorded a tremendous increase in terms of publications, as shown in Figure 1. The corresponding pie chart in the inset shows the associated fields placing "Engineering", "Energy", and "Material Sciences" as the most dominating topics. The investigation of the topic of PV soiling in the state of Qatar has been led by in-depth studies performed mainly in QEERI's OTF and has resulted in multiple research works, especially during the period 2020–2022.

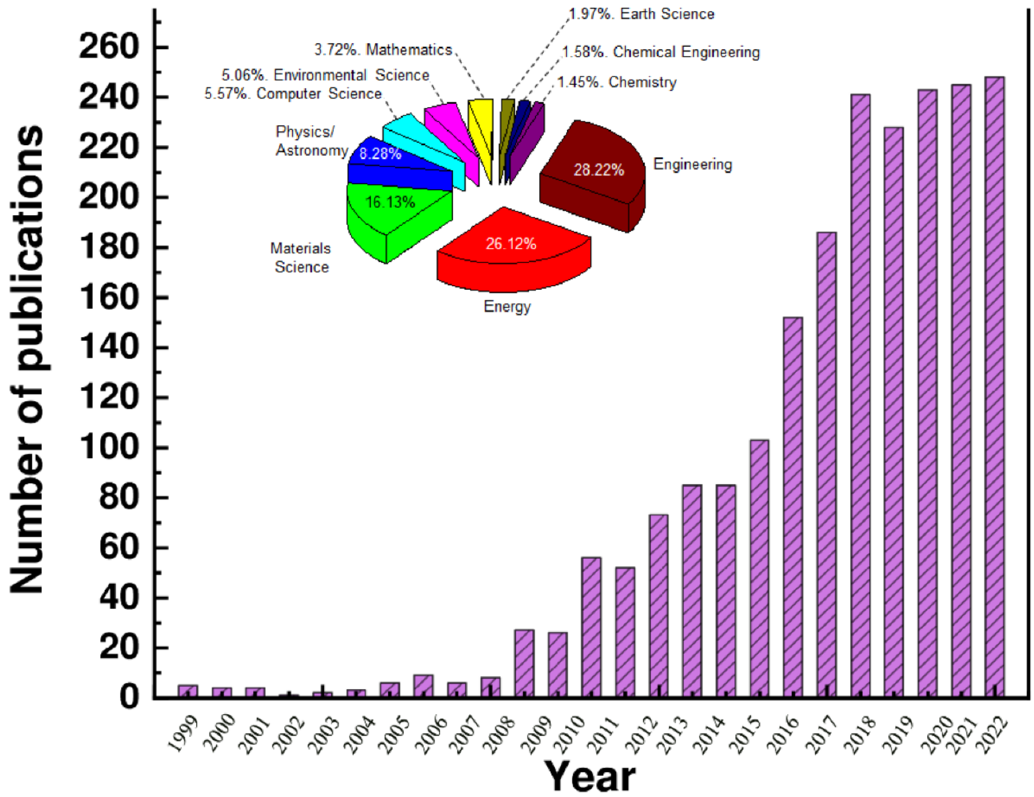

Figure 1. Number of refereed publications on PV soiling per year, along with their associated distribution of the used keywords. Data were collected from January 1999 to November 2022, mainly from Scopus®.

Within this report, the specific terminology is relevant. Hence, while the meaning of "soiling" is rather ambiguous, the terms "soil quantity" and/or "PV soiling loss" are used for their respective meaning. In fact, on a PV module, the decrease in light transmission (T%) due to dust accumulation does not perfectly match the associated PV power loss. More specifically, since solar cells have a selective spectral response, accumulated dust favors the attenuation of short wavelengths [1]. However, to avoid additional complexity, the attenuation of the transmitted light and the associated loss of the PV power are handled equivalently, unless stipulated otherwise, to avoid confusion. It was also reported that the correlation between PV power loss and dust accumulating mass had been occasionally found to be linearly proportional [2–4]. This is rather true during the first stages of the soiling process. Hence, once the surface becomes heavily soiled, additional dust particles cumulate onto the existing ones, therefore increasing the dust mass without necessarily affecting further the light transmission (i.e., flattening of T%) [5–7].

The geographical location also has a clear impact on the dust mass and, thus on the associated PV power loss. For instance, different types of dust (whether in terms of color, structure, size, etc.) have different impacts on light absorbance and/or transmittance. More specifically, for the same amount of dust, fine particles have a more dramatic effect on T% due to their higher cross-section (i.e., surface area to volume ratio). Similarly, the chemical composition and shape of the dust particles are critical factors that affect light absorption as well as light scattering properties [1]. Overall, the quantitative relationship between the cause and the effect (i.e., soiling mass vs. PV power loss) is linearly proportional for lightly soiled surfaces and nonlinear for heavily soiled ones (i.e., T% loss evolves more slowly than soil mass) [8,9]. Figure 2b shows a typical scenario of cleaned and non-cleaned PV modules after one month of outdoor exposure at the QEERI's OTF in Doha, Qatar.

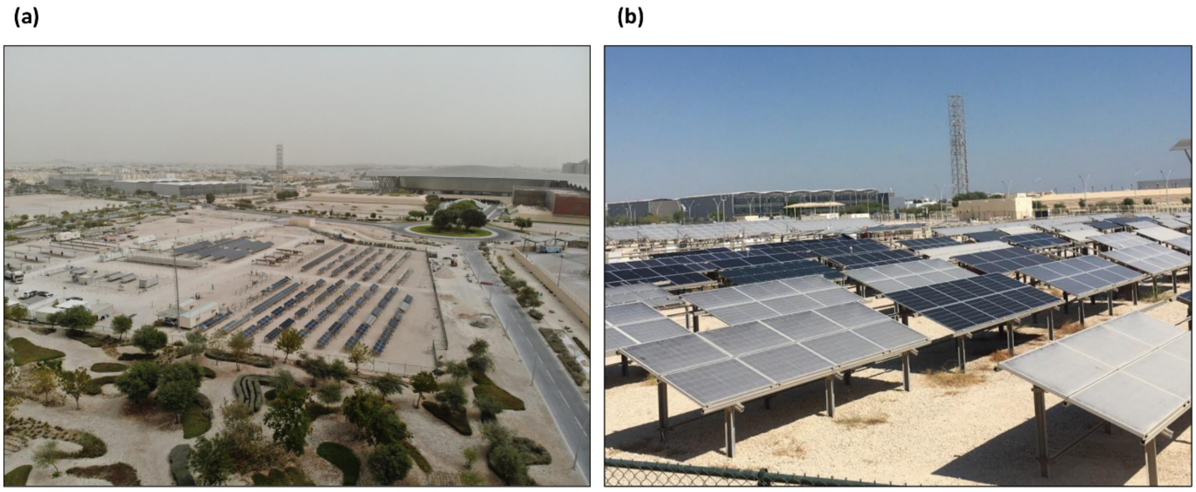

Figure 2. (**a**) Photo of the QEERI Outdoor Test Facility's area. (**b**) Cleaned vs. soiled PV modules surface after 30 days of exposure to outdoor conditions.

Succinctly, the soiling of PV surfaces relies on several parameters. First, it is impacted by site specificities, which include the location where the PV plant is installed, the associated concentration of airborne dust, the size of the particulate matter (PM), and the proportion of the soiling. Second, PV plant configuration and characteristics, which include PV module design, tilt angle, module's orientation and height, the level of shading, and the cleaning frequency. Third, the meteorological variations and seasons such as ambient temperature, wind speed and direction, level of relative humidity, and the frequency of dust storms. Fourth, morphological, structural, and physical properties of the dust particles: including size distribution, dust potency, level of cementation/caking/capillary, aging, type of dust, color, density, etc. Fifth, surface properties of the front glass of the PV module, adhesion forces, and cementation.

This comprehensive review summarizes key field-measurement findings and challenges in addressing PV soiling obtained during the last decade at the QEERI's OTF, located in the desert environment characterizing the state of Qatar. The manuscript is divided into ten distinct sections, each addressing different aspects of the subject matter. The introduction section presents the topic, provides background information describing the OTF, and highlights the significance of the review. Section 2 critically analyzes the impact of the soiling on solar radiation in Qatar, followed by the results related to the development of an in-house outdoor soiling microscope, in Section 3. In Section 4, the field measurements of PV soiling by commercially available sensors, including Mars^{TM} and Dust IQ are detailed. Section 5 describes in detail the soiling properties in the desert environment, including physical characteristics, the fundamentals of soiling processes, the influence of environmental parameters, the interaction between dust particles and the surface of PV modules, the parameters influencing condensation, and the dew mitigation by heating. Section 6 emphasizes the impact of PV soiling on PV performance (e.g., the effect of PV module surface orientation; the dust potency of PV soiling loss, and the seasonal variability of PV soiling in Qatar), and Section 7 develops the mitigation of PV soiling (including topics related to the manual and automated cleaning, the development of anti-soiling coating and the soiling mitigation potential by1-axis PV trackers are developed). The effect of soiling on bifacial PV modules and the energy cost and power production are discussed in Sections 8 and 9, respectively, and the renewable energy and soiling within the Gulf Cooperation Council (GCC) context is highlighted in Section 10. Lastly, the conclusion summarizes some key points discussed in the paper and offers a perspective on the topic, emphasizing its importance and potential impact.

Description of the OTF

Which solar-energy technologies work best in Qatar's climate? In 2012, this question led to the establishment of the Solar Test Facility (STF)—updated now to Outdoor Test Facility (OTF), at Qatar Science & Technology Park (QSTP). The OTF is an outdoor site hosting about 90 PV systems from several manufacturers. Located at: Latitude 25.327044025° (19′37.36″ N); Longitude 51.432901051° (25′58.44″ E); Sea Level 9 m. It extends over a 35,000 m^2 area and includes numerous types of supporting instruments for PV research, such as PV module test benches, trackers, and automated cleaning systems, among others. The OTF is continuously exposed to harsh environmental conditions, which makes it ideal to evaluate the efficiency of different PV systems under realistic conditions in Qatar. It is of paramount importance to evaluate the tested systems in terms of energy production and long-term reliability when exposed to elevated temperatures, high irradiation, intense humidity, and extreme soiling conditions, which all prevail throughout the year in the region (e.g., highest temperature: 42 °C, lowest temperature: 13 °C; Mean Temperature (Yearly): 27 °C; Mean RH (yearly): 56%; Precipitation: 0.2 mm; and Mean Wind speed (Yearly): 4 m/s). Koppen climate classification BWh (B = Arid; W = Desert; h = Hot arid).

A summary of typical equipment tested and installed at the OTF is the following:

- 38 crystalline silicon PV systems—mono-Si, multi-Si, bifacial
- 30 thin-film PV systems—CdTe, CIGS, µSi-aSi
- 4 hybrid PV systems—silicon hetero-junction, PERC, and TOPCon
- 7 concentrating PV systems
- Inverters—central, string, micro-inverters
- Trackers—1-axis, 2-axis
- Battery storage system (500 kWh)
- Linear Fresnel thermal collector
- Anti-soiling coatings

Meteo station with a Global Horizontal Irradiance (GHI), Direct Normal Irradiation (DNI), Total Normal Irradiance (TNI), Diffuse Horizontal Irradiation DHI, Plane of Array (POA), UV, and albedo.

The full-scale testing commenced at the OTF in March 2013. In 2016, QEERI took over its operation. Since 2013, QEERI has started developing a unique regional and worldwide expertise on PV soiling in desert climates, both from experimental and modeling/forecasting points of view.

2. Impact of the Soiling on Solar Radiation in Qatar

The continuous assessment of solar resources is needed throughout the lifetime of solar-power projects, from the feasibility analysis and design to the setup and management of the system. In QEERI, solar radiation measurement, modeling, and forecasting have been developed as main capabilities to help Qatar in deploying solar-energy-based projects. For instance, QEERI runs a network of 13 high-quality solar radiation-monitoring stations across the state of Qatar, measuring the three components of solar radiation (direct, global or total, and diffuse), in collaboration with the Qatar Meteorological Department (QMD). Since Qatar is a desert area, research works on solar radiation in QEERI have included the study of atmospheric dust or the accumulation of dust on sensor surfaces.

In this section, some of the main findings are presented. To study the effect of the atmospheric constituents on solar radiation, mainly atmospheric dust, and aerosols, the use of a LiDAR ceilometer in the estimation of the extinction of the beam or DNI has been investigated [10]. DNI, which is the energy coming directly from the sun disk on a unit area normal to the sun rays, varies along the sun line direction due to changes in the atmospheric contents such as clouds, dust, etc. Hence, the relation between the ceilometer signal and DNI under cloud-free conditions was studied, i.e., in conditions where clouds are absent and only dust and aerosols are present in the atmosphere.

Moreover, the daily variation of the integrated backscatter and the hourly averages of DNI for all the selected clear days of one year at local noon were investigated. Higher values of the integrated backscatter were seen in the summer season and during periods of dust storms indicating higher aerosol loads. DNI did not show clear seasonal changes during the year where higher radiation is usually expected in the summer due to the seasonal change in solar position. It showed, however, a significant reduction in periods of dust storms as well as lower values during the summer. A clear relationship was found between the two measurements, relating to the hourly so-called DNI clearness index.

As demonstrated in many studies [11–19], atmospheric aerosols can cause the soiling of PV modules by dry deposition under arid conditions. To quantify the effect of aerosols on the attenuation of solar radiation from the high atmosphere to the ground level, the Aerosol Optical Depth (AOD) parameter was used. AOD is also known to be well correlated with the particulate matter (PM) mass concentration [11–13]. AOD can be derived from satellite images combined with chemical transport models [14]; however, ground measurements remain the best method to acquire data locally with low uncertainties. In QEERI, we investigated a method of deriving the AOD using spectral ground measurements based on a multi-filter rotating shadow band radiometer (MFRSR) [15,16]. The collected data were fitted with linear regression and only the data that were correlated with a good fit were kept for the analysis. AOD values were estimated for several days, as per the method described above. The values were compared with AOD derived from the Copernicus Atmosphere Monitoring Service (CAMS) [17,18]. A subsequent study, related to solar radiation and dust accumulation effect on pyranometers in Qatar, was also conducted [19].

Subsequently, the soiling rate of pyranometers operating in Doha, Qatar, where atmospheric dust is abundant, and dust storms are frequent, was investigated. The experimental setup consisted of measuring GHI using two pyranometers: one acting as a reference with daily cleaning, and one test sensor with varying frequencies of cleaning. Figure 3 shows a sample period of the soling ratio quantified as the ratio of the daily averages of GHI measured by the soiled sensor to that by the reference sensor vs. the number of days since the last cleaning. The red line is the linear fit function quantifying the correlation between the soiling ratio and time, giving the value of the loss per day between 0.3% and 0.5% depending on the season. It is worth noting that more losses are seen in the summer when dust events are more common, and rainfall is practically absent in Qatar.

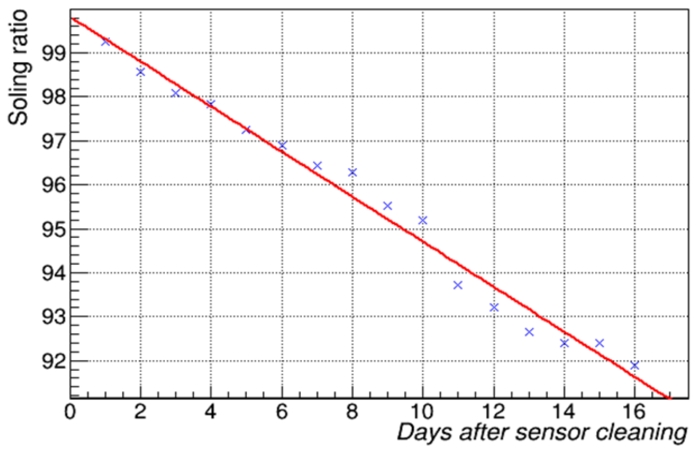

Figure 3. Soiling degree of a pyranometer operating in Doha, Qatar, showing the decrease of the measured global horizontal radiation per day due to sensor soiling.

3. Development of an In-House "Outdoor Soiling Microscope"

Among the various climate factors, wind speed, relative humidity, and PM concentration are the key factors influencing the soiling rate of photovoltaics [8]. However, to reach a higher correlation between these parameters and the soiling ratio, the frequency of measurement was increased by designing and fabricating an efficient device, operating in outdoor conditions, and is capable of quantifying the soiling rate in real time.

This device is called an "outdoor soiling microscope" and consists of an adapted digital microscope, connected to a computer. It can measure every few seconds the following parameters:

1. detect the onset of condensation,
2. detect the vanishing of the condensation,
3. measure the deposit dust particles that are above 10 µm^2 in size, and
4. measure their subsequent removal.

A glass microscope slide was fixed to the shroud protecting the front of the microscope. This system was then inverted in such a way that settled dust is visible through the slide by the microscope (Figure 4a). In doing so, images of ~0.9 µm/pixel were captured. A LED and a sheet of translucent paper were used to optimize the contrast of the dust particles (i.e., versus the background) and to provide continuous and uniform day and night lighting (Figure 4b, right panel). A program script was then developed to obtain images at a controlled time-interval.

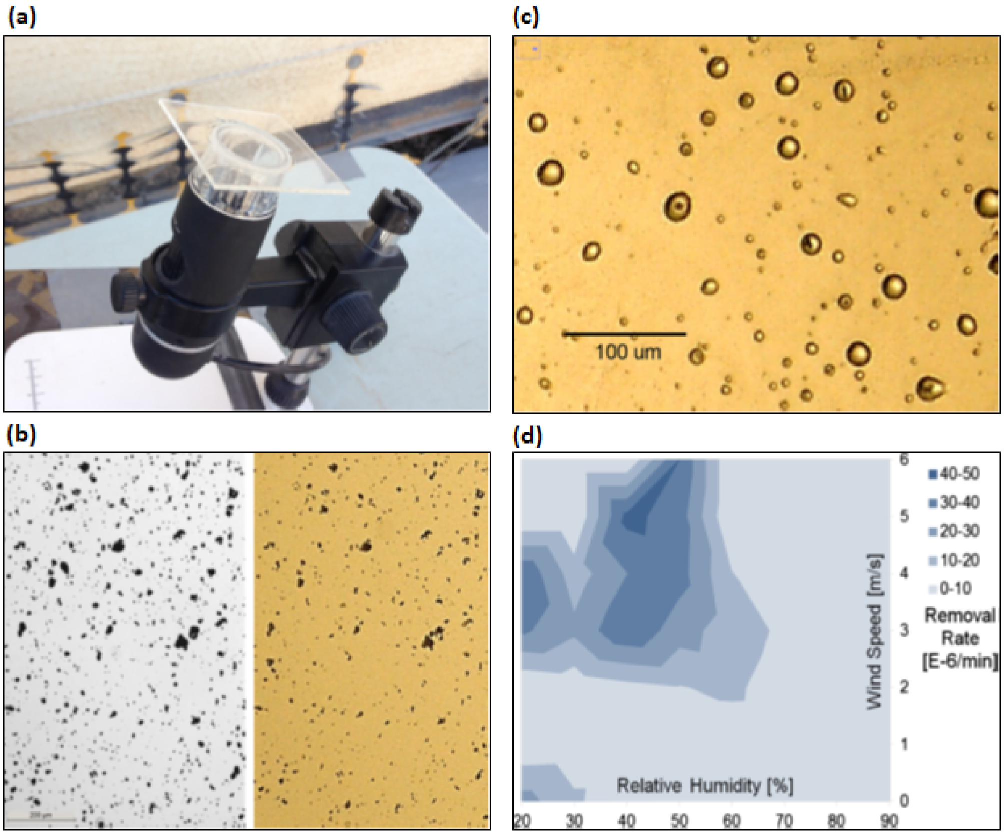

Figure 4. (**a**) Outdoor soiling microscope with a glass slide serving as a dust collection surface. (**b**) Lab microscope images of the same soiled surface (**left**) and the associated outdoor soiling microscope image (**right**). (**c**) Condensation droplets image was taken by the outdoor soiling microscope. (**d**) Removal rate vs. relative humidity and wind speed. Adapted from ref. [20].

The resolution of such a developed system was beyond expectations. It approached 2–3 pixels across, indicating that the detection of particles of about 2–3 µm in diameter was feasible. Moreover, the "outdoor soiling microscope" could detect condensation droplets that formed on the surface (Figure 4c), along with their life cycle, i.e., commencement (onset), development, and disappearance.

To better assess the impact of the environmental conditions, including wind speed, relative humidity, and airborne PM_{10} concentration on dust accumulation, and to point out the favorable conditions for natural cleaning, the data set between day hours (6:00 a.m. to 6:59 p.m.) and night were separated. The reason for this is that during the night, there was no net resuspension that took place (Figure 4d). Doing so, clear correlations were observed as follows:

(a) Increased relative humidity leads to a decrease in net resuspension.
(b) Increased PM_{10} concentration increases dust accumulation.
(c) Increased wind speed favors the natural cleaning by particle resuspension, and is triggered typically at 3 m/s.
(d) Increased wind speed above 4 m/s greatly favors the particles' resuspension.
(e) During the nighttime, no clear correlations could be claimed.

4. Field Measurement of PV Soiling by Mars^{TM} and Dust IQ Sensors

To provide high-quality soiling monitoring with high precision and reliability, a novel and cost-effective class of soiling sensors has recently emerged, showing a minimum need for water, cleaning, or maintenance when operated in the field. Some of these newly developed devices are already marketable, and their detection principle is based on the optical characteristics of the dust particles. Two brands, namely Atonometrics' Mars soiling sensor and Kipp & Zonen's Dust IQ, are the pioneering commercial devices for PV soiling monitoring.

In the same vein as the ongoing work on the outdoor soiling microscope, we have demonstrated field-test data measurements of the Mars™ soiling sensor installed in two different geographical locations in Qatar (Figure 5), characterized by hot, sunny, and dusty conditions.

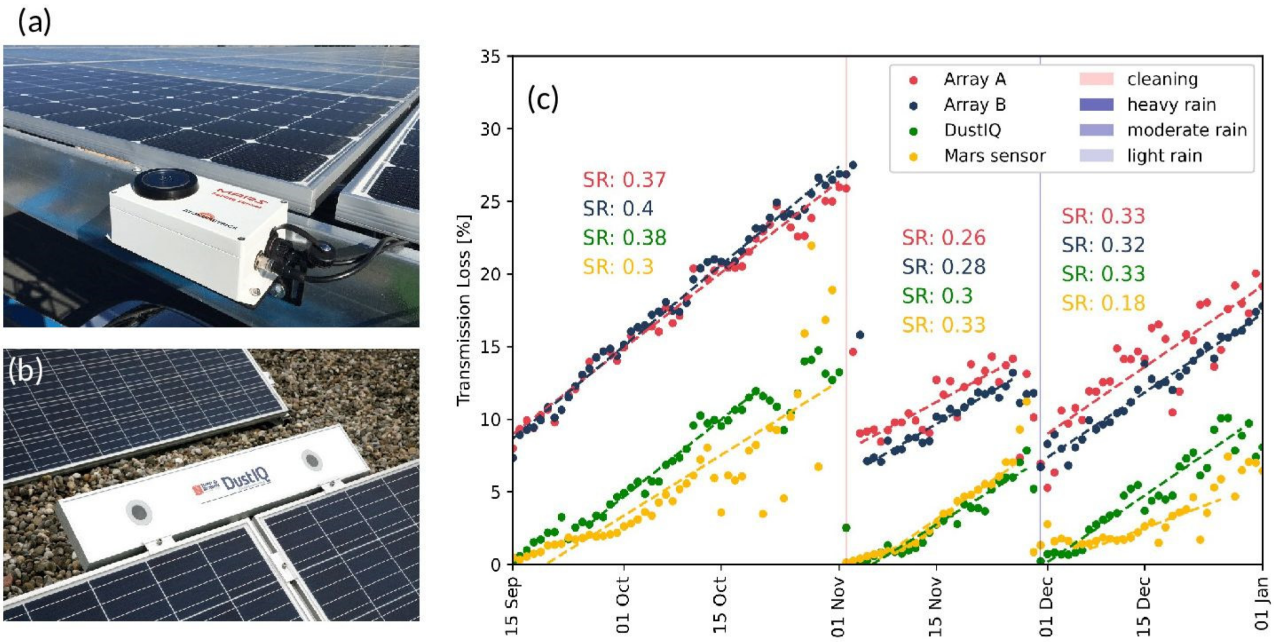

Figure 5. (**a**) Mars™ soiling sensor and (**b**) Dust IQ sensor at PV test field along with clean/soiled reference cell pair. (**c**) Summary of the daily soiling rate (SR) measured from the data of the Mars™ during different periods. Results were compared to the PV arrays' daily power losses obtained from two different arrays. Adapted from ref. [21].

Field data showed high accuracy and very good correlations between the traditional soiling measurements using a cleaned/uncleaned reference cell and the Mars™ output, therefore demonstrating it field-test validity. Similarly, the same study was conducted with a commercial Dust IQ to detect daily soiling, and a high correlation between these sensors and a PV cell was demonstrated, especially during the cold season. The mismatch of the soiling ratio (ΔSR) measured from the two methods, namely the Mars™/DustIQ and the conventional clean/soiled reference cell pair method, was found to be less than 0.11% [21] as shown in Figure 6.

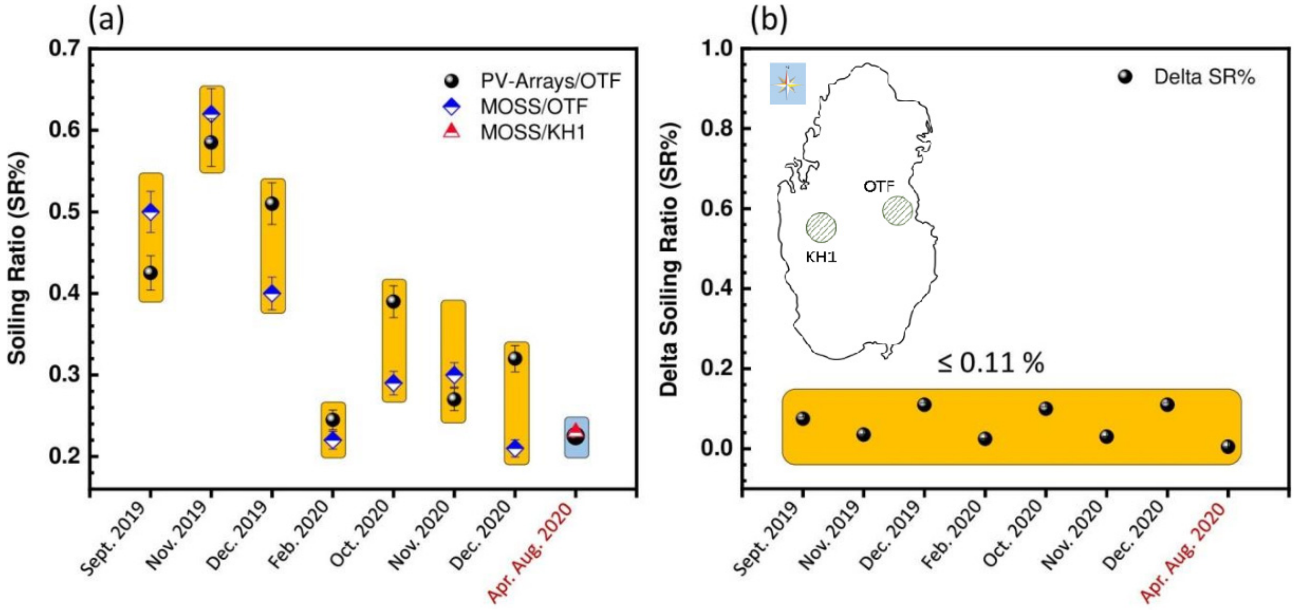

Figure 6. (**a**) Summary of the calculated SR %, and (**b**) mismatch (ΔSR) between the data analyzed from the Mars^{TM} sensor and PV arrays. Inset in (**b**) is the Qatar map showing the two sites where the Mars^{TM} and/or Dust IQ sensors were operated. Adapted from Ref. [21].

5. Understanding of the Soiling Properties in the Desert Environment

5.1. Physical Characteristics

The physical and chemical properties of soiling impact dust particles' interactions with the PV surface, and the level of involvement of environmental factors. Hence, the physical properties, including the structural, optical, morphological, magnetic, and chemical composition of dust particles collected from PV panel surfaces installed in OTF were systematically investigated.

As shown in the SEM in Figure 7a, various particle sizes and morphologies could be observed; however, the mean size might be considered at around 20 µm with a dominant spherical-like shape, overall [22]. Two shape factors were noticed, one approaching ~1 for the small particles which were mainly spherical, and the second ones of about ~3.5, similar to that observed in Saudi Arabia [23] and African Sahara (~3) [24–29].

The chemical elemental composition of these desert dust particles was probed using EDS (Figure 7b,c) which revealed rather a non-uniform distribution and various concentrations of these compositions, within the same set of particles.

As observed in OTF, potassium traces could be associated with sea salt as the state of Qatar is a peninsula located in the Arabian Gulf. Sulfur can be associated with anhydrite or gypsum component ($CaSO_4$), etc. [25,26]. The XRD analysis of these dust particles was displayed in Figure 7d and the phase chemical formula was summarized in [22]. The quantitative analysis led to some dominant composites, including akermanite ($Ca_2Mg(SiO_7)$), wuestite (FeO), sillimanite ($Al_2(SiO_4)O$), olivine ($Mg_2(SiO_4)$), and calcite ($CaCO_3$) and quartz (SiO_2) given the desert nature of the soils.

Some traces of titanium were also detected and were attributed to a geographical factor which is the proximity of the OTF to the urban zone, where Ti may originate from the resuspension of dust particles induced by heavy traffic (i.e., tires) (Figure 8) [30–35].

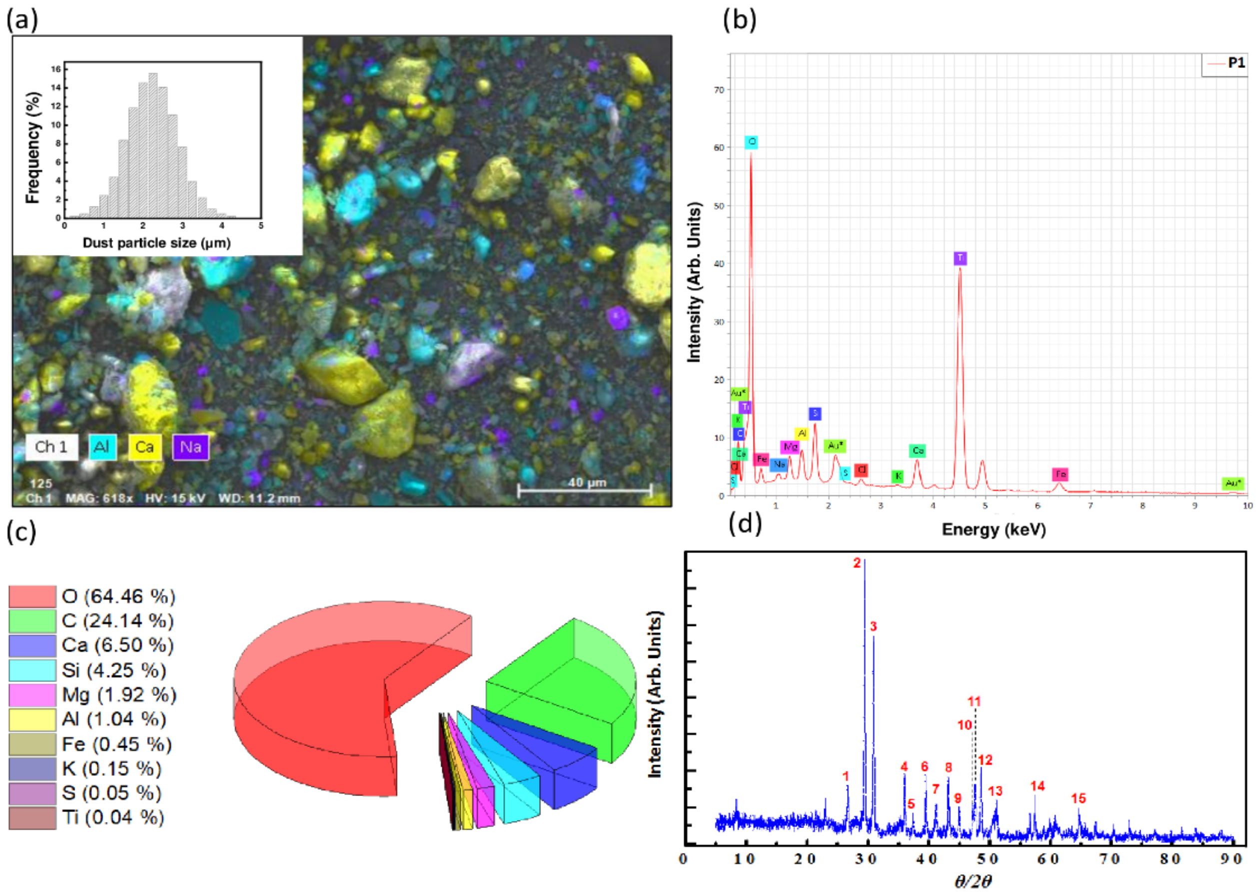

Figure 7. (**a**) Typical SEM micrograph of the desert dust particles collected from the OTF PV panels. An example of a particle-size-distribution histogram is shown in the inset. (**b**) Energy dispersive X-rays spectra, and (**c**) the associated chemical composition of the dust particles. (**d**) Representative X-ray diffraction pattern of dust particles. Adapted from ref. [22].

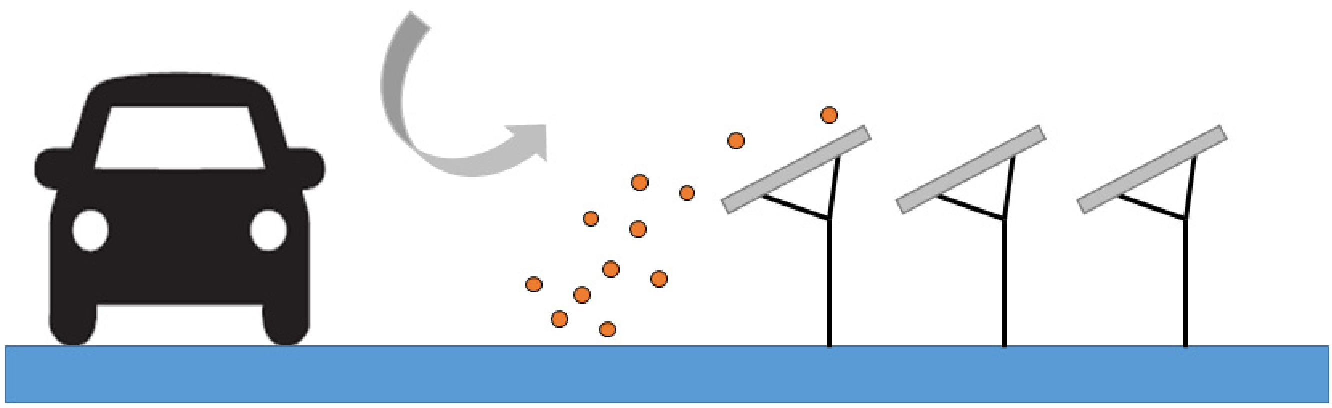

Figure 8. Schematic of site adaption highlighting the effect of urban traffic on soiling.

Figure 9 shows a comprehensive literature review of particles accumulating on outdoor surfaces [29–35].

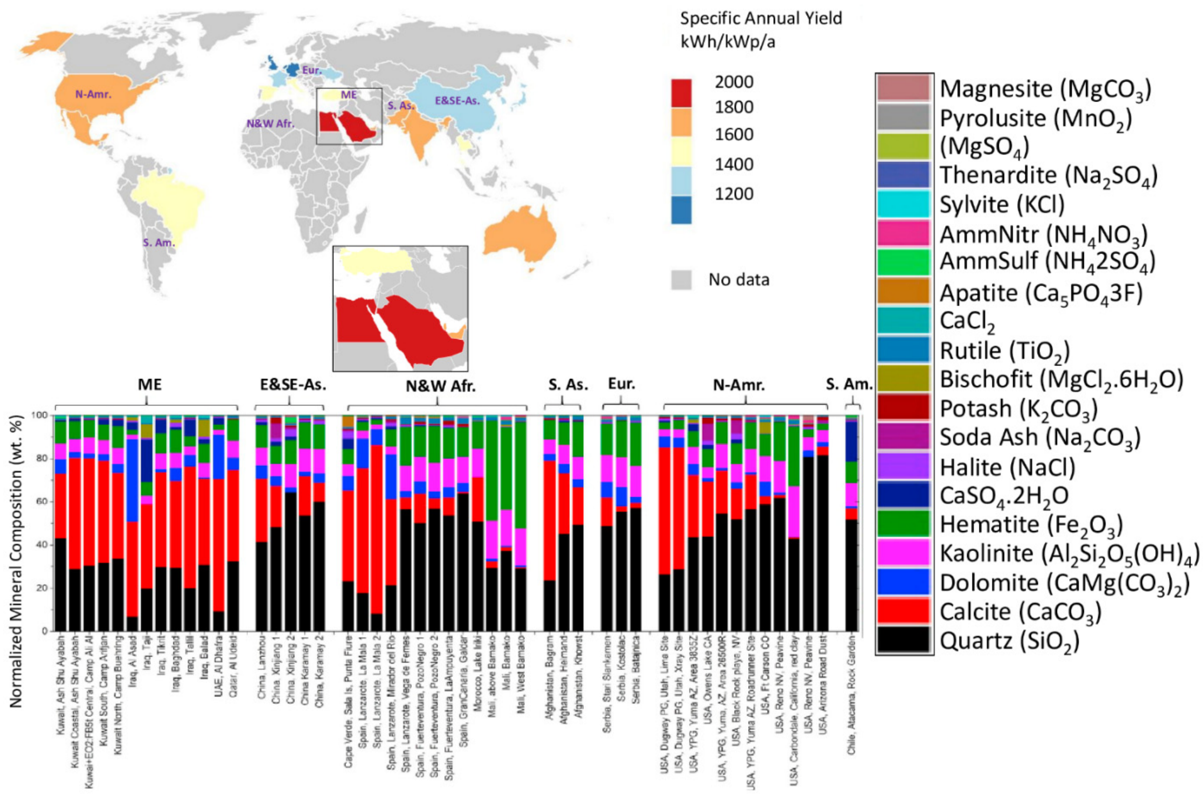

Figure 9. Various chemical mineral compositions based on XRD analysis of dust particles collected from the ground of various regions over the world [27,28]. Statistics in this figure are adapted from [35].

5.2. Fundamentals of Soiling Processes

In this study, a deep and detailed overview of the fundamentals of soiling processes has been provided by investigating the interplay between the macroscale environmental parameters and the microscale properties of dust particles [35,36]. Figure 10 shows a set of the main influencing factors on the PV soiling phenomenon. The color code is as follows:

(a) Macroscopic environmental factors in blue.
(b) Microscopic environmental factors in green.
(c) Manageable impacting factors are in orange. The latter includes PV module design, glass-surface properties, etc.

Although the focus was devoted to PV module surfaces, the same reasoning applies to concentrated solar-power (CSP) mirrors as well. Moreover, dust particle adhesion forces and how they vary with cementation, caking and capillary aging, dust removal, and accumulation mechanisms, and their correlations with environmental parameters, were discussed. This study may serve as a basic guide and a starting step towards optimizing the various developed mitigation strategies, including module cleaning, anti-magnetic, and anti-soiling coating processes.

The main findings suggest the following:

(a) The concentration of airborne dust was found to be a key factor in forecasting the soiling rates over different geographical locations over medium to long periods [33]. For a shorter period, such as day-to-day variation, additional environmental parameters play a more important role. Moreover, three parameters were found to constitute the best PV soiling predictors, namely (i) the airborne dust concentration, (ii) the duration of the dry periods, and (iii) the rainfall frequency.
(b) The adhesion forces between the flat glass surface and the dust particles were dominated by capillary forces in the presence of moisture, which may also prevent their resuspension by the wind.

(c) van der Waals forces dominated the adhesion in the case of dry conditions, though gravity and electrostatic forces could be considered negligible.
(d) Under windy conditions, when drag forces were present, rolling was the dominant detachment mechanism for particles.

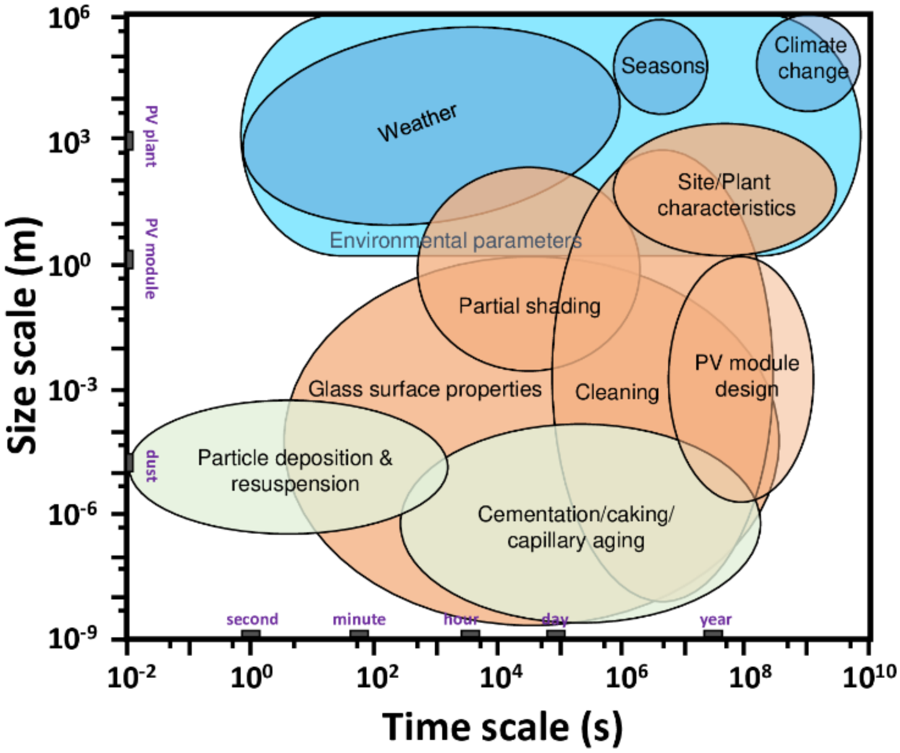

Figure 10. Influencing factors of the PV soiling: correlational system between the size scale in meters and the time scale in seconds, showing the complexity of the PV soiling phenomenon and its high degrees of freedom. Adapted from ref. [35].

5.2.1. Influence of Environmental Parameters

Considering environmental conditions with low rainfall events and no condensation/cementation phenomena, the wind will be the prevailing natural cleaning process. For the dust particles to be effectively detached from the surface, the hydrodynamic forces (in addition to the wall shear stress) must beat the adhesion forces. When present, rain may efficiently clean surfaces. The correlation between rain events and surface cleaning was investigated in reference [33], and this study demonstrated that a threshold of minimum precipitated water was necessary for effective cleaning. This threshold was dependent on the velocity of the droplet, dust composition, surface wettability, tilt angle, and dust adhesion forces, and varied from a daily minimum of 0.3 mm [33] to 5 mm [36,37], 7–8 mm [38] and even up to 20 mm [39].

It was demonstrated that environmental factors greatly influence the various mechanisms of dust particle deposition and its adhesion/removal properties.

These environmental factors, including temperature (T), relative humidity (RH), wind speed (WS), and the concentration of airborne dust, vary along the day following a regular pattern [40] as follows:

a. Ambient temperature: lower during the night period, higher during the daytime.
b. PV module temperature: lower during the night period, higher during daytime (at even higher and lower levels than ambient temperature).
c. Relative humidity (RH): higher during the night period, lower during the day. Please note that the temperature of the air governs the concentration of the water-vapor saturation.

d. Wind speed (WS): lower during the night period (rarely above 3 m/s) and higher levels during the day going above 5 m/s.
e. PM_{10} concentration: there are no established patterns as observed for other parameters. However, statistically, we record higher mean levels during the night period than during the day. The maximum values of PM_{10} were observed early morning (6–8 am).

5.2.2. Interaction between Dust Particle and PV Module Surface

The accumulation of dust and the associated soiling rate is mainly governed by the behavior of the dust particle in terms of its interaction with the PV surface, and more particularly, by its rebound and resuspension versus its deposition (this will be more detailed in Section 5.3). These interactions are subjected to the surface properties, removal forces (e.g., by wind), and the particle/surface adhesion at large. Figure 11 depicts the main important soiling mechanisms, while Figure 12 summarizes the typical particle adhesion forces.

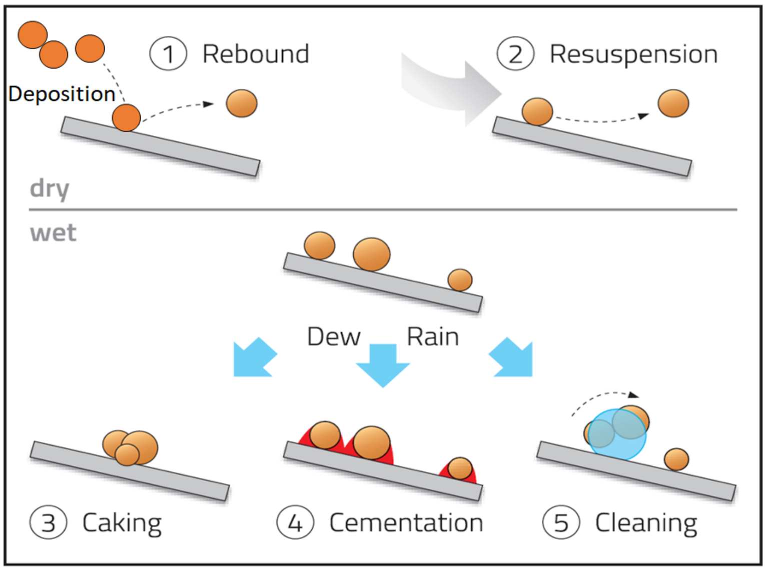

Figure 11. Schematic Illustration of important soiling mechanisms. Adapted from reference [40].

Typically, the nature of the adhesion forces is surface' property dependent, and has several forms:

(a) Rough and smooth glass surface: van der Waals forces.
(b) Hydrophobic and hydrophilic surface: capillary forces.
(c) Charged particles: Electrostatic forces.
(d) Gravity, when assuming the weight of the particle sphere.

Properly addressing the type of interactions between the dust particle and the PV module surface is of paramount importance for two main reasons: (i) understanding the involved interactions and their correlation with the dust composition, and (ii) appropriate development of the most efficient cleaning method (dry/wet, robotic, etc.). In [41], the main fundamental adhesion forces, namely gravitational, van der Waal, capillary and electrostatic, were reported experimentally. These four forces dominate the early stages of the soiling mechanism. The findings demonstrated that under high relative humidity, the adhesion process is governed by capillary force, while during dry conditions, van der Waal force dominates (see Table 1). The main findings are detailed below:

Table 1. Experimentally measured adhesion forces between dust particles and glass substrate in OTF (Doha, Qatar) [41].

Type of Adhesion Force	Measured Value (Averaged over Samples)
Capillary	1951 nN
Van der Waals	39.4 nN in humid conditions, 324 nN in dry air
Electrostatic	0.026 nN
Gravitational	0.0018 nN

Obtained results showed that the attraction mechanisms acting on the particle/surface under humid environmental conditions were 98% capillary, and 2% van der Waal, whereas the gravitational and electrostatic, were negligible. Please note that gravitational forces are often negligible for particles size below 500 µm [42–49].

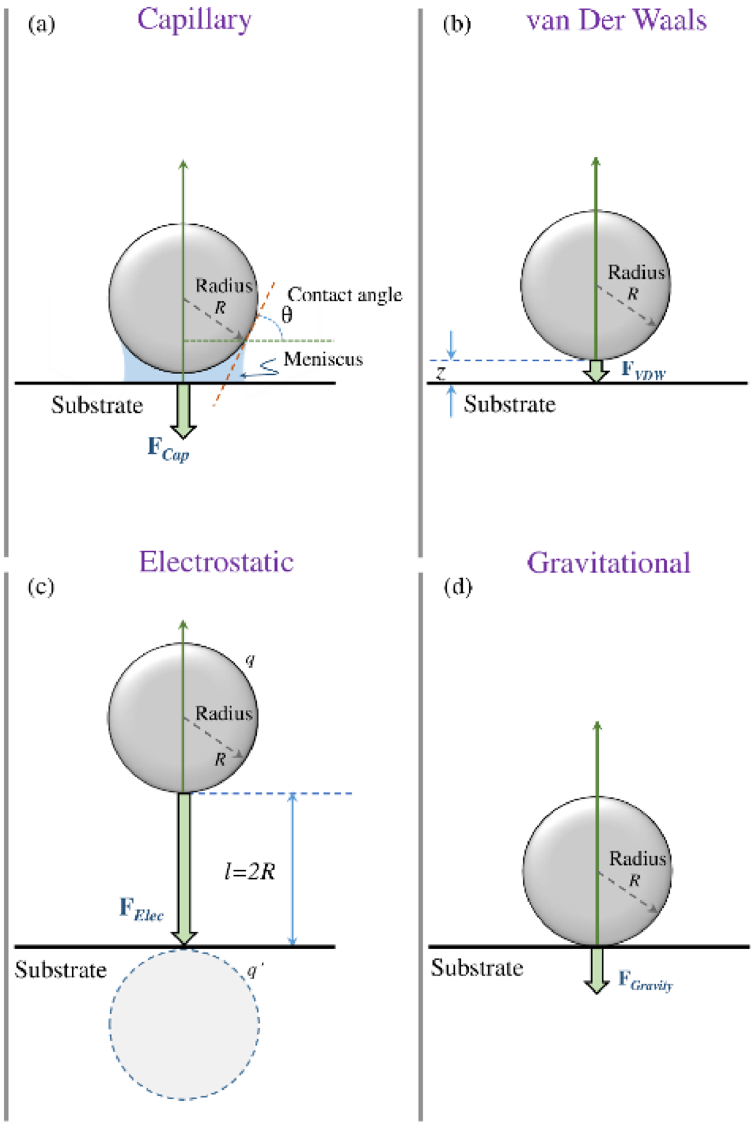

Figure 12. Representative scheme of the (**a**) capillary, (**b**) van der Waals, (**c**) Electrostatic, and (**d**) Gravitational forces between a dust particle and a glass substrate.

5.3. Parameters Influencing Condensation

The investigation of the daily patterns of environmental parameters conducted in the QEERI/OTF site has demonstrated that relative humidity increased during nighttime, whereas wind speed and air temperature decreased (Figure 13) [49]. During the nighttime, and because of the radiative cooling phenomenon, PV modules' temperature decreases (owing to their high IR emissivity) below the ambient one, which favors dew and water capillary formation, especially during the period just before dawn. In [50], experimental evidence has been provided demonstrating that the PV modules installed in OTF (Qatar) showed 5.1 K degrees below ambient temperature during the night.

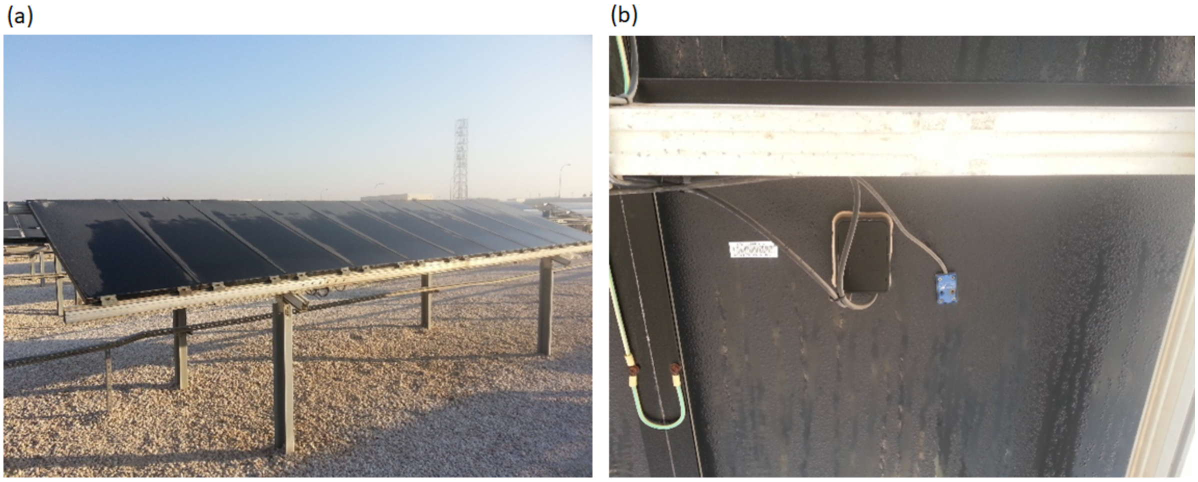

Figure 13. (**a**) Photos taken early in the morning of water condensation formed at the front glass of the PV array. (**b**) Water condensation on the backside of a PV module installed at QEERI/OTF. Adapted from [49].

The successive drying of the PV panel after the dew period increased dust particles' adhesion, by triggering their cementation, caking, and capillary aging. In the latter scenario, mechanical cleaning was needed. According to this study, it was demonstrated that soiling occurs principally during the night period. Consequently, any cleaning (or self-cleaning) through wind may occur during midday time when the wind is at its maximum, and the surface is dry. However, this was true only for weakly attached particles that were not subjected to dew.

Experimentally, a naturally soiled glass coupon in the OTF field was still showing microscopic water droplets even when its temperature was superior to the dew point by about 14 °C. The water droplets were then growing when the gradient temperature passed to 8 °C and completely covered the glass surface when it was about ∼1–2 °C. However, while using a hydrophobic coupon, namely PTFE, microscopic water droplets were formed even when its surface was warmer than the dew point, but unlike the glass coupon, PTFE stopped the droplet growth and inhibited the flooding as the coupon was cooled. Figure 14 shows representative images taken by the developed outdoor soiling microscope (OSM). In ambient conditions, water droplets were formed on the surfaces of both glass and PTFE for 4 h, at nighttime.

Three processes govern the rate of dust accumulation onto a given surface (PV module or CSP mirrors), namely:

(a) "Deposition" refers to the particle in the atmosphere impacting the surface.
(b) "Rebound" is when this particle is rapidly rebounding from this surface without adhering.
(c) "Resuspension" occurs once this particle is resuspended by wind [35,49].

Each of these processes may be signified as a dust flux rate, which translates the mass of the dust quantity per area and time units:

$$Accumulation = Deposition - Rebound - Resuspension$$

In [8,51], the accumulated soiling mass and the associated PV power loss were investigated along with the dust particle mechanics. Under desert environmental conditions in

Qatar, dust particle sizes were between a few to tens of microns, while wind speed rarely exceeded a few meters/s. The main deposition mechanism was hence sedimentation, and consequently, the associated PV soiling was subjected to the tilt angle of the PV module. The sedimentation was more critical for larger particles. However, there was no universal model describing particle rebound, although resuspension was dependent on particle size (large particles were efficiently lifted off by the wind, unlike small ones) and was also favored by high wind speed as it was dependent on the square of flow (/wind) speed. Inclining the PV surface toward the airflow should promote the resuspension of particles, yet very few studies on the impact of the azimuth orientation (i.e., wind direction over the surface) on PV soiling were conducted, especially in real-world conditions. Thus, deeper research in this regard is necessary to study the mitigating of soiling by placing the surface of modules in different levels of airflow (e.g., by changing the height of the PV modules at elevated values). For more details, the reader was invited to consult references [8,49,51].

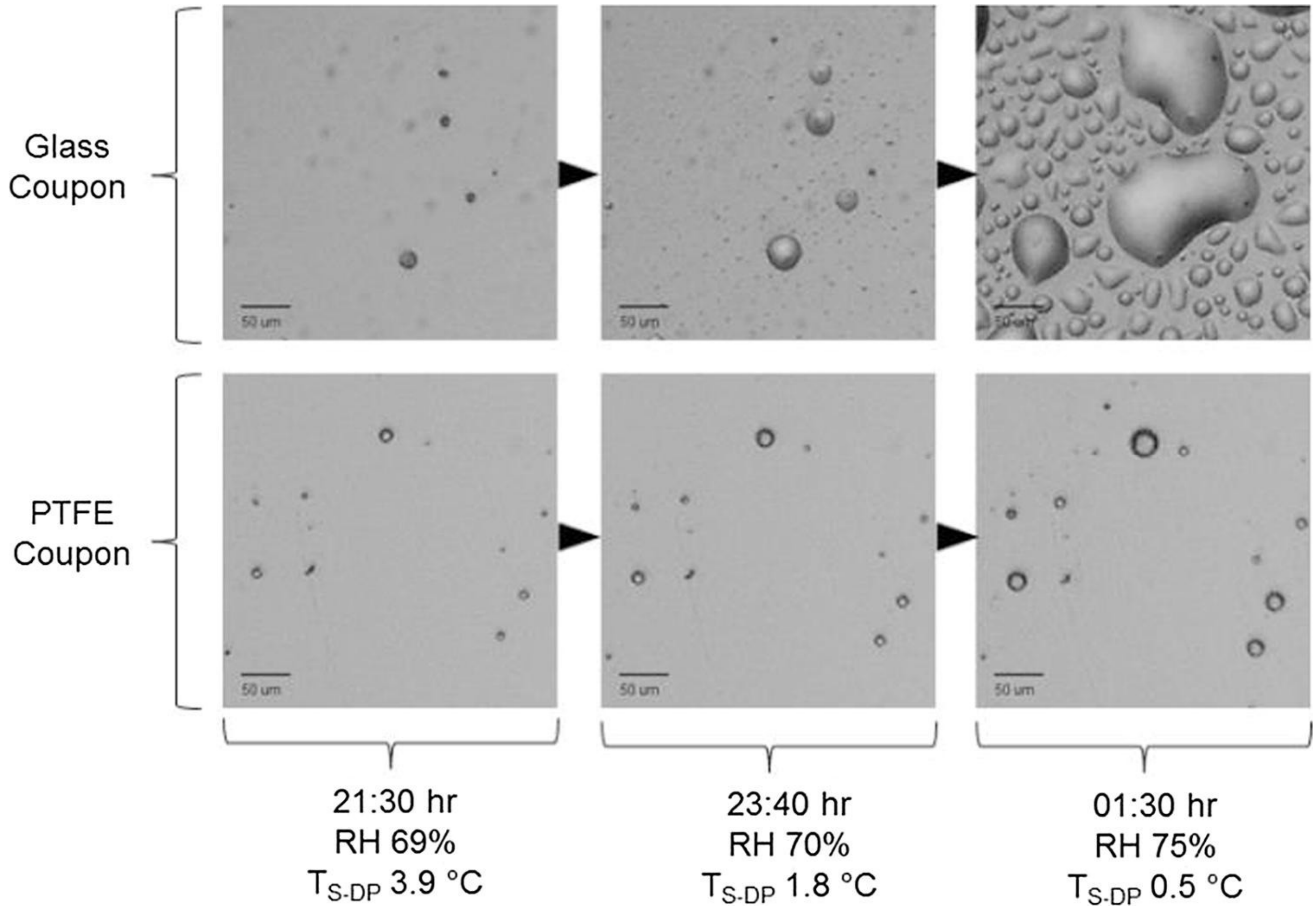

Figure 14. Optical OSM photos of various droplets formed on glass and PTFE surfaces. Ambient conditions and 4 h during nighttime conditions were used. Adapted from Ref. [49].

5.4. Dew Mitigation by Heating

Thermal treatment or heating the PV module to mitigate dew depositions can effectively reduce the cementation process [52,53]. Condensation usually occurs before sunrise when the ambient temperature is higher than the module temperature due to radiative cooling, and when the relative humidity is high. On days of dew prevalence, the soiling levels are recorded to be considerably higher than on dry days. Consequently, recent soiling reduction methods have been introduced by avoiding moisture through passive and active sheet heating. They may include thermal energy generated from thermal collectors (such as phase change materials) installed at the backside of PV models, active heating of PV modules using heat exchangers, or radiative cooling methods. Active heat with reasonably high energy suggested a soil reduction of up to 65%, but it seems that there are no data, simulations, or realistic assumptions on the financial viability of these warming strategies. These thermal systems can be retrofitted on PV modules and may serve dual advantages for devices; for daytime, cooling will result in increased energy yield whereas, for nigh time, heating will result in reduced condensation and hence cementation. The potential cleaning cost for implementation is less than 80 EUR/m^2 for the PCM-based heating technique [53].

6. Impact of PV Soiling on PV Performance

6.1. Effect of PV Module Surface Orientation

One of the most critical parameters affecting the dust accumulation rate is the PV module orientation (Figure 15). This parameter is crucial too in the optimization of the overall PV performance. Commonly, only the sedimentation is taken into account, unless the conditions are rather windy with WS above ~3 m/s. Notably, the dust particle properties collected after a dust storm may differ from the dust particle properties collected on a normal day. The former will depend on the wind direction from where the dust storm is coming [54–65].

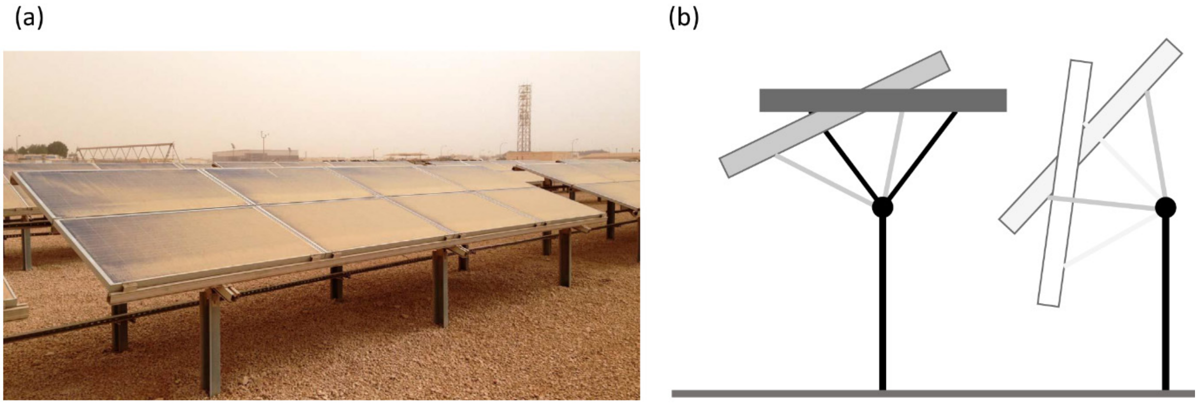

Figure 15. (**a**) Dust accumulation on a PV array following a sandstorm in OTF, Doha. (**b**) Schematic of various surface tilt angles.

Sedimentation, which is affected by gravity, is dependent on the tilt angle, while inertial and resuspension, which are rather affected by wind, are dependent on both tilt angle and azimuth, the latter is the angle of the vertical axis of the PV module surface exposed to the horizontal airflow.

The accurate effect of the tilt angle on the soiling phenomenon is difficult to generalize because of the similarities between the deposition and resuspension trends (see Figure 10), and the competition between these two mechanisms is subject to the conditions specific to each situation.

Overall, results in desert environments show that deposition is more important than resuspension, and PV soiling is mainly controlled by sedimentation. In the experiments in wind-tunnel analysis, which tend to employ and investigate faster airflow speeds, it was found that soiling is more significant on moderately tilted surfaces rather than horizontal ones [65]. Ongoing research, initiated on glass coupons, is currently being conducted in OTF to identify the exact contribution of deposition and resuspension on PV modules as a function of the tilt angle.

In [61], we experimentally investigated the dust accumulation on glass coupons, positioned tilted perpendicularly to the wind. Two environments were studied, one based on a wind tunnel and the second representing the real-world conditions at the OTF site (Figure 16).

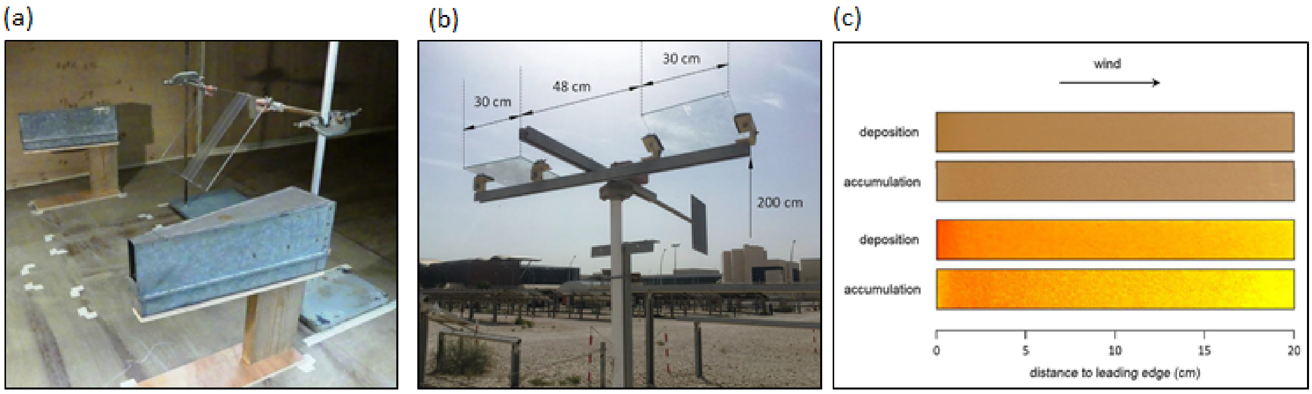

Figure 16. (**a**) Setup of wind-tunnel tests. (**b**) Field soiling wind performed in OTF: the left coupon is at 0° tilt, and the right coupon is at −22° facing downwind. (**c**) Wind-tunnel imaging: structure of soiling layer along the glass coupon in cm (WS = 2 m·s^{-1}, tilt angle = 30°). Adapted from ref. [61].

Parallel to this experimental investigation, computational fluid dynamics (CFD) modeling was performed to interpret the obtained experimental results. In OTF, it was found that:

(a) The maximum dust deposition in the field test occurred at 45° facing the wind (this deposition was calculated as the total particles impacting the coupon surface).
(b) The maximum accumulation occurred at 22° away from the wind (the accumulation was calculated as the total particles remaining on the coupon surface).

The difference between the two is due to the detached particles from the coupons when they were tilted toward the wind, which was dependent on two main parameters, namely the wind speed (wind flow velocity in this case), and the shear rate at the glass surface. The findings indicate that to decrease the soiling at night, a one-axis PV tracker (developed in Section 7.3) should be stowed at a maximum tilt angle, facing the wind.

Furthermore, to obtain more insights into soiling physics, the difference between dust deposition and its accumulation was studied. In this study, tilt angles were relative to the horizontal toward the wind direction. For instance, 45° indicates tilted facing the oncoming wind; 0° means horizontal; −45° implies tilted away from the oncoming wind (i.e., put downwind or backward, see Figure 16).

To simulate typical desert dust including that of Qatar, a dust-cloud producer dispersing "Belgian-Brabantian" dust, with 37 µm average size particle, was used in the wind-tunnel experiments [61–65]. However, as large dust particles tend to resuspend, mainly finer particles were found to accumulate on surfaces in this experiment [61–65]. At 5 m/s wind speed (which was the targeted speed in OTF), the average median diameter of the accumulated dust particles measured on the coupons was 20 µm, matching closely the 15 µm of the dust size collected from PV modules at OTF [8].

For the coupons that were facing the wind direction, the accumulation of the dust particles was found to decrease with respect to WS and with respect to the tilt angle too. Soiling reached its maximum of −22°, i.e., when the surface of the coupon was tilted slowly away from the wind. Moreover, tilting toward the wind was found to decrease the soiling as compared to the same tilt angle away from the wind. This indicates that for PV trackers that rotate commonly around ±45° or ±60°, a tangible reduction of dust accumulation could be achieved "for free," especially during windy nights, by keeping the PV modules at a maximum tilt (ideally vertically) facing the wind.

6.2. Dust Potency of PV Soiling Loss

To assess the effect of dust deposition and accumulation on the PV panel surfaces, various techniques and approaches have been developed. Most of the studies available in the relevant literature discussed the performance degradation of the soiled PV modules during a given period of exposure [66–68]. However, only very few studies have been conducted on the quantification of the accumulated dust mass (ADM) effect on PV power loss [69,70]. The dust accumulation rate, at a particular location, was found to vary substantially with respect to the exposure time, season, and weather patterns [71,72]. Some works have been dedicated to depicting the experimental correlation between the ADM and the light transmission loss % [73–75], while others focused on the theoretical dependency between ADM and PV power loss [76].

In collaboration with Texas A&M University in Qatar (TAMUQ), a broader and deeper analysis approach to conclude an accurate quantitative relationship between dust-induced PV performance loss and the ADM and its physical and chemical properties was conducted [71]. Figure 17 summarizes the monthly average daily dust accumulation rate (DAR) patterns and weather and environmental variables that include airborne PM_{10}, WS, and RH%, during the sampling period from January 2015 to October 2016, inclusively.

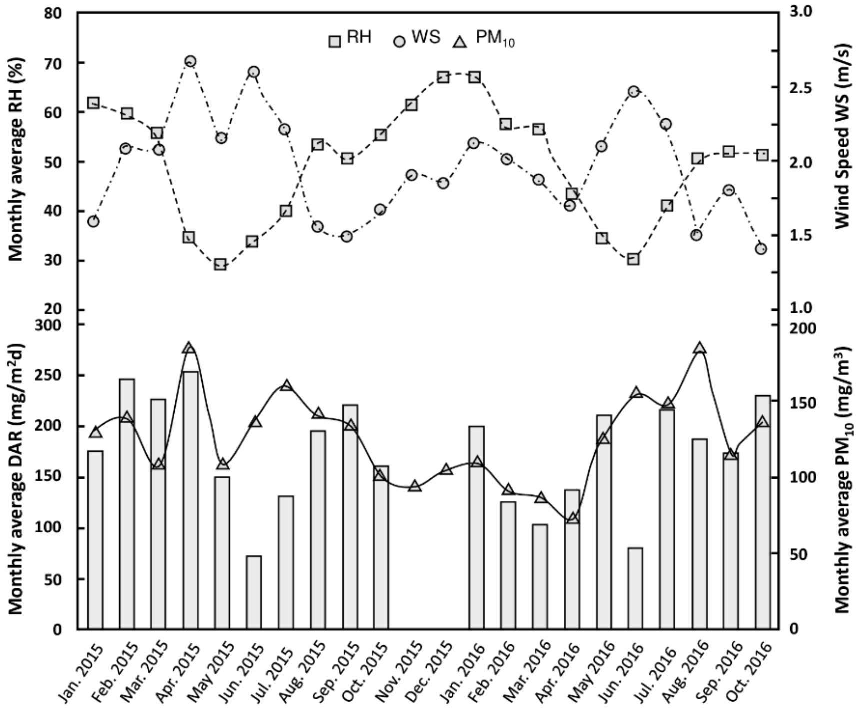

Figure 17. Variation of monthly average DAR, RH%, PM_{10}, and WS from January 2015 to October 2016. Adapted from ref. [71].

Depending on the dominant meteorological conditions, the monthly average DAR was found to vary from 75 to 250 mg/m^2/day, with the lowest value observed during June and was attributed to the high WS, and low RH% during this month, although higher PM_{10} was observed during this month, which contributes to increasing the resuspension of the dust particles and therefore decreasing the net-accumulation of the dust on the PV surface [36,51]. This value of 75 mg/m^2/day corresponded to a relative PV power loss of about 0.20%. Interestingly, the average daily DAR generally follows the same pattern as the airborne PM_{10} concentration, excluding the months with high WS where the DAR values are less. The findings indicate that higher DAR favors higher dust accumulation, and hence higher PV soiling was observed at elevated PM_{10} concentration, higher RH%, and lower WS parameters [71].

6.3. Seasonal Variability of PV Soiling in Qatar

The seasonal variation must be considered if one wants to forecast the soiling behavior, accurately estimate the PV power yield, and plan an optimized cleaning schedule. However, for a given geographical spot, a timescale of a single annual soiling rate might often be inadequate to precisely understand, and quantify the PV soiling, and the associated PV power loss given the temporal variability of the soiling ratio from one year to another [76–78].

Observing and identifying the seasonal soiling trends permits us to predict with better accuracy the associated total annual soiling losses. This is even true when optimizing the cleaning schedule. The quantification of the daily soiling and the accurate prediction of its rate before forecasting the seasonal soiling patterns and the corresponding average yearly energy loss is paramount in designing an economically profitable PV plant.

In an ongoing study with TAMUQ, we have in-depth studied the seasonal patterns of PV soiling in the desert conditions characterizing the state of Qatar, for six (6) years [73]. The field data related to PV power along with meteorological factors from 2014 to 2019 have been systematically and continuously recorded.

The cleanness index (CI) is defined as a measure of a PV module's cleanness during a 24-h day. It is calculated as:

$$\mathrm{CI} = \frac{\mathrm{PR}_{\mathrm{T\_corr\_soiled}}}{\mathrm{PR}_{\mathrm{T\_corr\_clean}}} \tag{1}$$

where $\mathrm{PR}_{\mathrm{T\_corr\_clean}}$ is the daily temperature-corrected performance ratio of a clean PV array. $\mathrm{PR}_{\mathrm{T\_corr\_soiled}}$ is the quotidian temperature-corrected performance ratio of the PV array for which the cleanness is being assessed. The daily soiling rate is hence the daily variation of CI, i.e., "ΔCI" and is plotted in Figure 18.

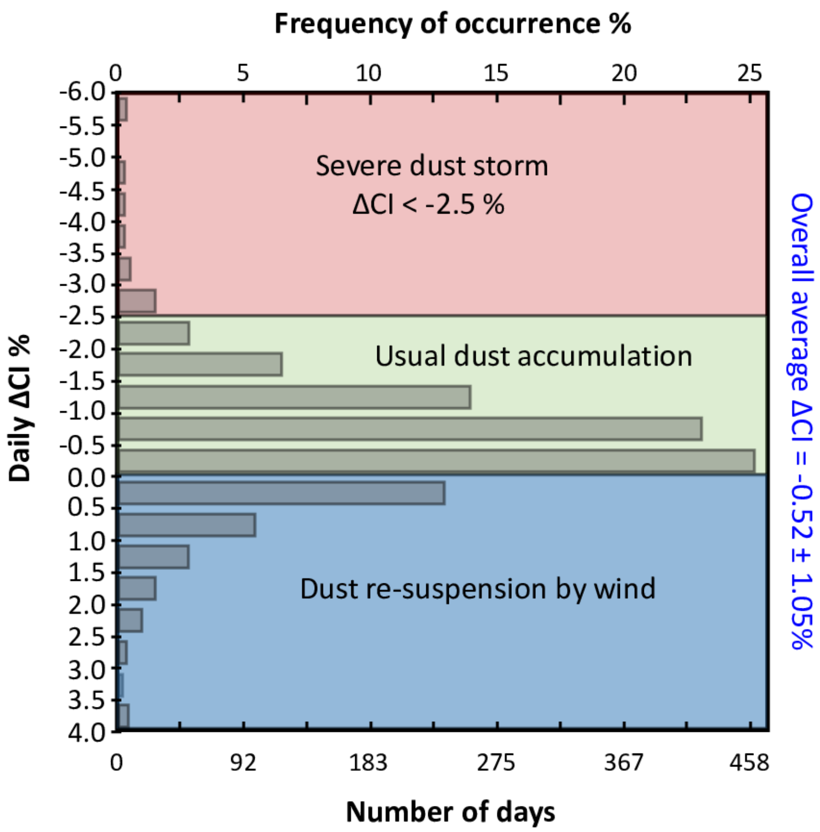

Figure 18. Daily ΔCI % as a function of the number of days. Adapted from ref. [73].

For the day number n, the ΔCI which represents the difference of CI of the nth day and (n − 1)th one is:

$$\Delta\mathrm{CI}_{\mathrm{n}} = \mathrm{CI}_{\mathrm{n}} - \mathrm{CI}_{\mathrm{n}-1} \tag{2}$$

Figure 19 shows the time series of soiling-induced PV performance loss in terms of CI for every month of the study period. CI, representing the PV soiling ratio, decreased substantially with respect to the exposure time. The soiled PV array was cleaned every second month (in addition to the natural cleaning by rain), which has restored the CI to unity.

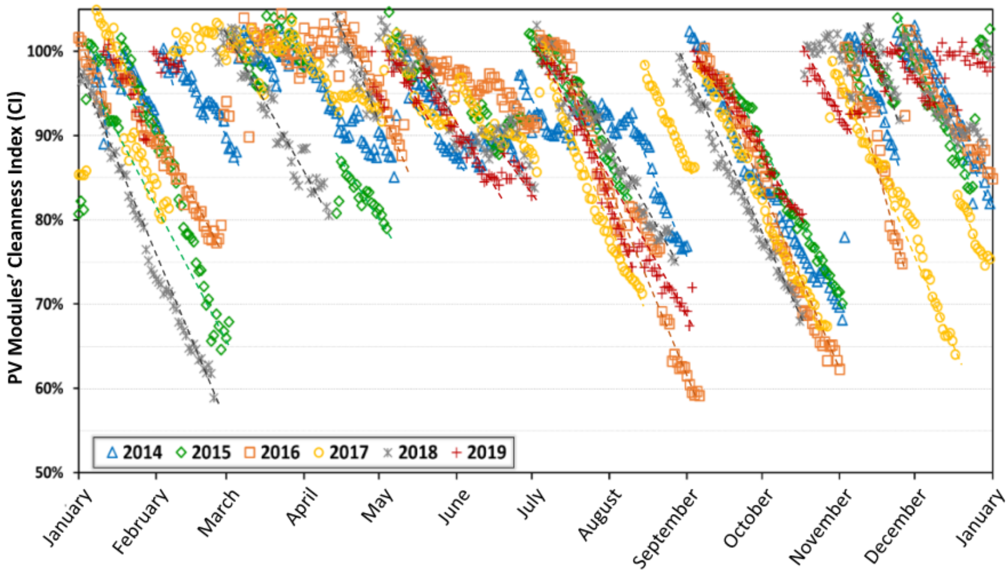

Figure 19. PV cleanness index (CI) of the soiled PV array as a function of time (bi-monthly cleaned modules) from 2014 to 2019. Adapted from ref. [73].

a. The summer season (July–October) showed a decrease in CI by about 20% per month and this occurs consistently during only dry periods year after year.
b. Typically, for the bi-monthly cleaned panels, the associated PV power loss was about 15%/ month, with a clearly defined seasonal pattern.
c. During wet seasons, i.e., rainy periods, the CI reduction was limited to 10% due to cleaning triggered by the rain that prevents the accumulation of dust for more extended periods.
d. Wet season with higher rain rates such as in 2017 has shown a better CI (even close to unity) as compared, for example, to the same season in 2015.
e. Although the monthly PV soiling varied noticeably, the associated seasonal trends were more or less respected and the yearly change was less significant.
f. Cold, rainy, or warm seasons show different soiling as they are impacted by environmental factors.
g. A threshold of a minimum of 3 mm rainfall was found to be the required value to fully clean the PV modules.
h. Summer months are characterized by dust storms (DS), yet their impact when they occur during the winter season was found to be more impactful. DS days increase the annual average soiling rate by 23%.

This study highlighted the pattern of seasonal soiling in a desert environment characterizing the state of Qatar, which may help PV industrial operators in designing an efficient cleaning schedule and therefore results in a significant decrease in solar-power generation losses and the associated plant operational and maintenance costs, leading to a global revenue increase.

7. Mitigation of PV Soiling

7.1. Manual and Automated Cleaning

To date, there is no passive anti-soiling technology (based on surface coatings) that has demonstrated a complete elimination of the cleaning event. Moreover, no cleaning process is currently universally recommended, as it depends on the availability of on-site resources, the economics, and the required frequency of cleaning.

Generally, cleaning methods are classified into manual, semi-automatic, and fully automatic (Figure 20). An additional differentiation could be made between:

(a) Dry-cleaning-based technologies: presently they are available only for PV and not CSP. These cleaning methods are applied in the desert and arid environments where water sources are rare,
(b) Wet-cleaning-based technologies: these methods are usually favored owing to their efficiency and due to the low potential of surface damage [41,79–82].

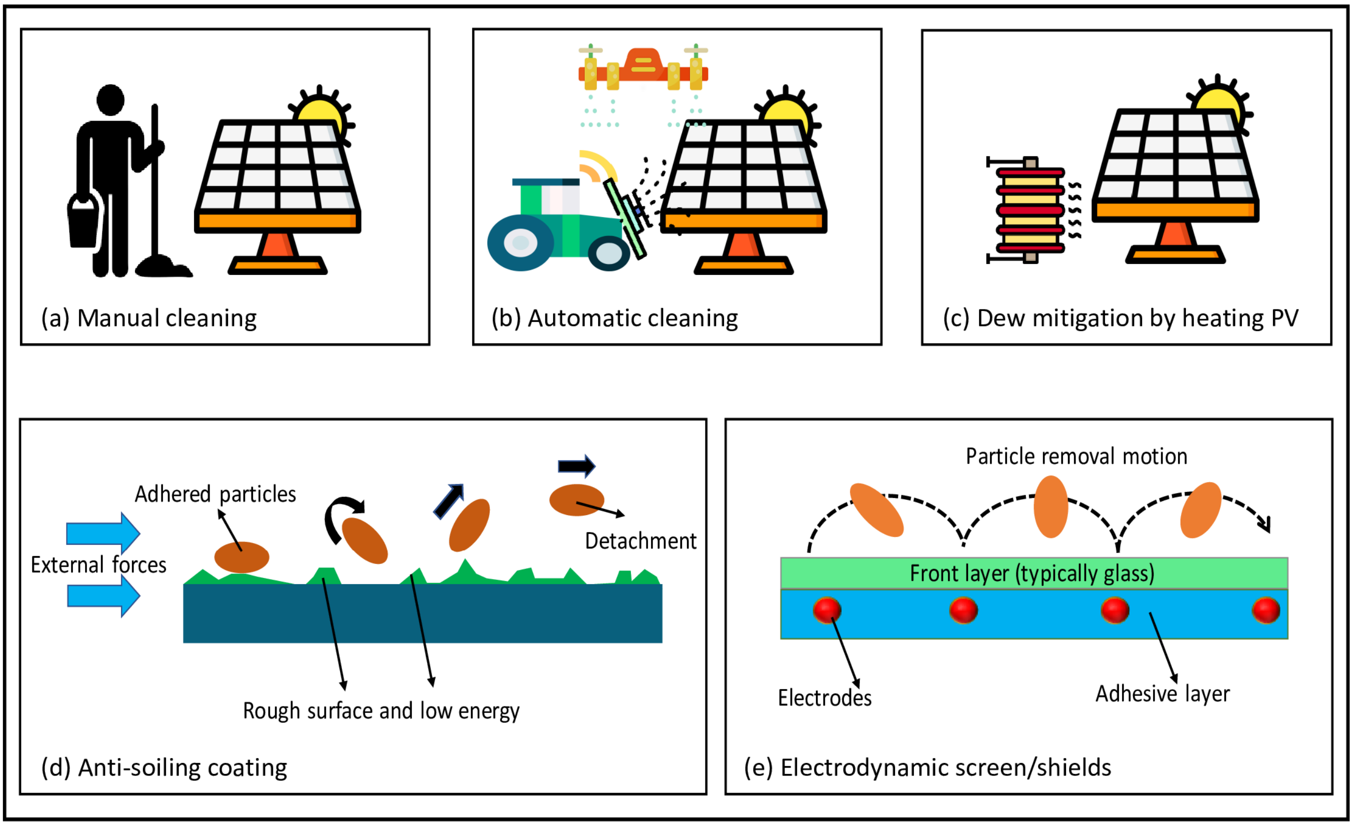

Figure 20. Soiling Mitigation Technologies (**a**) manual cleaning (**b**) automated cleaning (**c**) dew mitigation for cementation control using heating (**d**) anti-soling coating and (**e**) electrodynamic screen or shields for repelling dust particles.

Cleaning of the first mega-watt PV project in the region originally relied on manual cleaning; however, when robotic cleaning was introduced, the latter was faced with reliability issues due to the harsh soiling environment in the Arabian desert. Nevertheless, in the past three years, almost 100% of robotic cleaning was implemented in MW-scale PV projects. This has generated several questions regarding cleaning frequency, dust removal efficiency, and cleaning homogeneity over the whole PV surface area. Moreover, the concern of the possibility that PV surface coating shall be abraded by the robot movement was raised. All these concerns, whether technical, economic, or commercial, shall be further investigated to determine the best mode of cleaning where reliability and OPEX must be intact.

Nonetheless, for the present total solar power, the automated cleaning industry share is about 1.9 GW currently and represents only 0.13%. However, this is expected to expand to 6.1 GW by the end of the current year 2023 [40,83] thanks to the modern developments of dry and fully automated robots, which are increasingly implemented into the PV plant design (Figure 21).

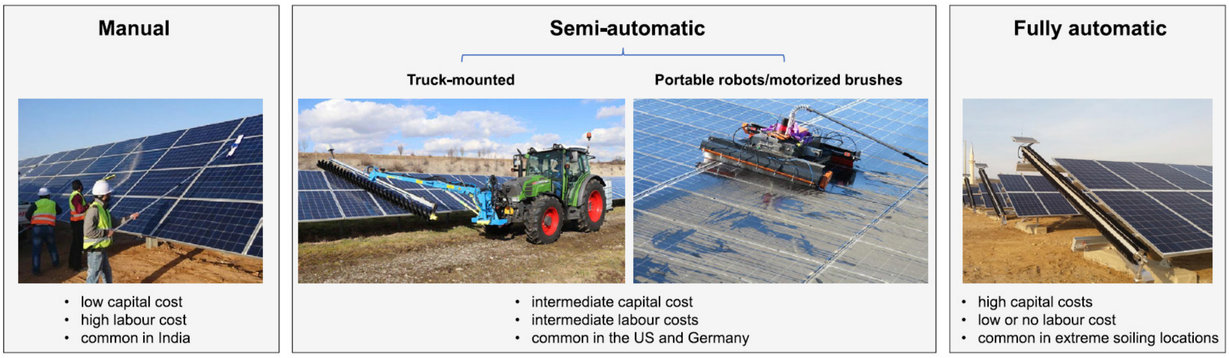

Figure 21. Photos examples showing the main cleaning technologies, namely manual (**left**), semi-automatic (**middle**, including truck-mounted portable robot models), and (**right**) fully automatic. Reproduced from [40].

A minimum of eight factors (Table 2) influence the decision on which optimal cleaning technology to adopt. This includes the nature of the soiling itself; the mass related to the dust deposition; the availability of water resources; the accessibility to the PV site; the configuration and architecture of the PV system, which includes tracking vs. fixed technologies, roof vs. ground-mounted configuration; the labor cost, the cost of the needed equipment and tools; and the conditions relative to the feed-in contract. Attempts are made to determine an appropriate cleaning frequency based on the identification of soiling levels and their forecasting. The potential cost for applying automated cleaning is in the range of 2.4–8.2 EUR/m^2 with a possible soiling reduction of more than 95% [40,80–85]. The current ongoing efforts are focused now to identify an optimized cleaning schedule for Qatar using a machine learning forecasting model that is based on soiling-detection rate and local environmental conditions.

Table 2. Soiling reduction potential and costs for selected soiling mitigation technologies. Adapted from references [84,85].

Mitigation Technology	Potential Optimum Reduction of Soiling Rates	Costs	Potential Limitations	Application Scenario
Fully automated cleaning	>95%	2.4–8.2 €/m^2	Integration in plant design	PV utility scale, ground mounted
Anti-soiling coatings: - Applied by glass manufacturer - Retro-fit	<<80% (literature review) <20%–50% (authors estimate) 32% reported for commercial coating	<2 €/m^2	Performance dependent on location and season, degradation by cleaning and environmental stresses	Utility scale, residential, ground mounted and rooftop, BiPV, CSP + extra benefit from AR property
Tracking	<40%–60%	N.A.	Integration in plant process; involves additional costs	Utility scale, ground mounted, state of the art in CSP
Electrodynamic screen/shield	<<98% (laboratory) 32% reported for 2-year study in Saudi Arabia	<30 €/m^2	Expensive, large-scale application needs to be proven	BiPV, island systems, street lighting, rooftop, CSP
Heating - PCM - Active cell heating - PVT	<20%–60%	<80 €/m^2 (PCM) N.A.	Expensive, large-scale application needs to be developed	BiPV, island systems, street lighting, rooftop installations + extra benefit from cooling during day for PCM + PVT
Optimized PV module design and orientation	<65%	%0 €/Wp	Integration into mass production	Utility scale, rooftop installations
Site adaption	unknown, site specific	N.A.	Low experience, research needed	Utility scale PV and CSP

7.2. Development of Anti-Soiling Coating (ASC)

Anti-soiling coatings (ASC) is one of the leading soiling mitigation techniques thoroughly researched in the community. It is applied to the front glass of CSP mirrors and PV panels to minimize the soiling and decrease the need for frequent cleaning. Ideally, ASCs must be optically transparent, with antireflection and self-cleaning ability, non-toxic, stable, durable, cost-effective, and deployable at an industrial level. This rends ASC somehow the "Holy Grail" of the soiling community [86]. This passive cleaning strategy has seen minimal consumer adoption as it does not remove the necessity of cleaning but rather provides prolonged cleaning periods between successive cleaning events [87–95]. The soiling level in the field declined by as much as 80% using anti-soiling coatings. For extended times, nevertheless, typical anti-soiling efficiency is usually much weaker (for instance 20–50%) and may grow worse than bare front cover depending on the quality of coating, regional weather, and deterioration level. The major motivation, however, for anti-soiling costs comes from its potential cost which is less than 2 EUR/m^2 [40]. Table 3 summarizes the state of the art of main PV soiling research and market.

However, limitations arising from physical phenomena must be considered:

(a) Geographical and seasonal variation [96].
(b) Particle adhesion physics [65,97–100].
(c) Durability/Stability [101–107].

The long-term stability and reliability of passive coatings are difficult to foresee, and the PV-community has attempted to define standard methodologies to assess them a priori, e.g., VDI 3956-1 or IEC 62788-7-3.

Table 3. PV Soiling Research and Market—State of the Art.

A—International and Regional Efforts		
	Institution	**Details of the Product**
Regional		
[108]	KISR (Kuwait)	Field Testing
[109]	KAUST (KSA)	Field Testing/Product Development—Cleaning Robot NOMADD
[110]	DEWA (UAE)	Field Testing
[8]	QEERI (Qatar)	Field Testing/Dust characterization/Fundamental Research/Anti-soiling coatings/Statistical Models
International		
[111]	Fraunhofer	PV Soiling and Degradation
[112]	NREL	Photovoltaic Module Soiling Map, Forecasting Tools, Fundamental Research, Abrasion, Soiling, etc.
[113]	AtaMoS-Tec—Chile project: ISC Konstanz, Fraunhofer Chile, SERC and French CEA, INES	Photovoltaic Module Soiling study, Forecasting Tools, Fundamental Research
[114]	SANDIA LABS/Arizona State University	Soiling Loss Research, PV Reliability
[115]	University of Colorado/Pontifícia Universidade Católica de Minas Gerais (Brasil)	Soiling Science and Technology, Coatings and Films
[116]	DLR Raumfahrtmanagement (the German Aerospace Center)	Airborne soiling measurements and product development
[117]	TÜV Rheinland (Germany)	Anti-soiling coatings
[118]	International PV Quality Assurance Task Force (PVQAT)	Sensors and Monitoring, Cleaning Solutions and Anti-Reflective and Anti-Soiling Coatings, Standardization

Table 3. *Cont.*

A—International and Regional Efforts		
	Institution	**Details of the Product**
[119]	European Cooperation in Science and Technology (COST) "inDust" program	International effort by WHO, WMO, ECMWF—Dust monitoring and forecasting models
B—Cleaning Solutions (Automatic, Robotic)		
[109]	NOMADD	Desert, Utility Scale, Dry Brush
[120]	Eccopia	Desert, Utility Scale, Dry Brush
[121]	Washpanel	Moderate Climate, Rooftops, Wet cleaning
[122]	Greenbotics/ SunPower	General Utility, Wet Cleaning
[123]	First Solar/ DEWA	Desert, Utility Scale, Dry Brush
[124]	Serbot Gekko	Moderate Climate, Rooftops, Wet cleaning
[125]	SOLRIDER	General Utility, Wet Cleaning
[126]	Enerwhere	Desert, Rooftops,
[127]	BladeRanger	General Utility, Dry Cleaning
C—Soiling Sensors		
[128]	German Aerospace Center	Qfly (Airborne soiling measurement of entire solar fields)
[129]	Campbell Scientific	Soiling Index Measurement Solution
[130]	Kipp and Zonen	DustIQ Soiling Monitoring System
[131]	Nor-Cal Controls	MaxSun Soiling Station
[123]	NRG	Soiling Measurement Kit
[124]	Ammonit	Soiling Measurement Kit
[132]	Atonometrics	Mars Optical Soiling Sensor
[133]	Kintech Engineering	Soiling Measurement Kit
D—Smart PV monitoring systems (IoT/Data analytics)		
[134]	Alternative Energy Solutions	AES PIT (Uses machine learning/advanced data analysis platform)
[135]	InnoEnergy	Solar Energy 3.0 (Smart PV monitoring esp. for detecting degradations)
[136]	Solar IoT platform	TrackSo (Data-driven predictive and condition monitoring)
E—Anti-Soiling Coatings		
[137]	CSD Nano	MoreSun Multi-Function Coating (Electrodynamic Dust Shield, EDS)
[138]	Anti-Soiling (AS) coating	DSM (Surface Modified Anti-Soiling Coating)
[139]	Hydrophil AS coating	Lotus Leaf Coatings (HydroPhillic Coatings)

7.3. Anti-Soiling Potential of 1-Axis PV Trackers

Expectedly, the surface tilt angle has a direct impact on soiling, where fewer dust particles may accumulate at steep angles, while more particles resuspend by tilting toward the wind direction, hence, the PV soiling can be efficiently reduced using a one-axis tracker stowed vertically at night, or by taking advantage from windy periods to help cleaning the PV modules by tilting the surface at angles that promote the particle resuspension. In [126], we experimented with the latter concept where a desert field study was conducted with 360° rotating 1-axis trackers and 10 cm × 10 cm glass coupons (Figure 22), with the trackers' axis of rotation (East-West) approximately perpendicular to the dominant wind direction. It was found that a 41% soiling reduction was achieved on average by stowing vertically (90°) at night and a further 9% reduction by stowing upside-down (180°). However, attempts to promote dust removal by tilting coupons toward the wind during daytime windy periods achieved only around 5% soiling reduction (compared to the tracker remaining "on Sun") and this approach would also sacrifice solar-energy harvest. In conclusion, modifying the 1-axis trackers to stow the PV modules at an angle $\geq 90°$ during the night period may efficiently reduce the PV soiling in the desert environment, while using these trackers to favor wind cleaning does not show to be an efficient process. Further validation of the findings is recommended using full-scale PV systems, in a variety of environmental conditions, especially where condensation is more prevalent and wind speeds higher.

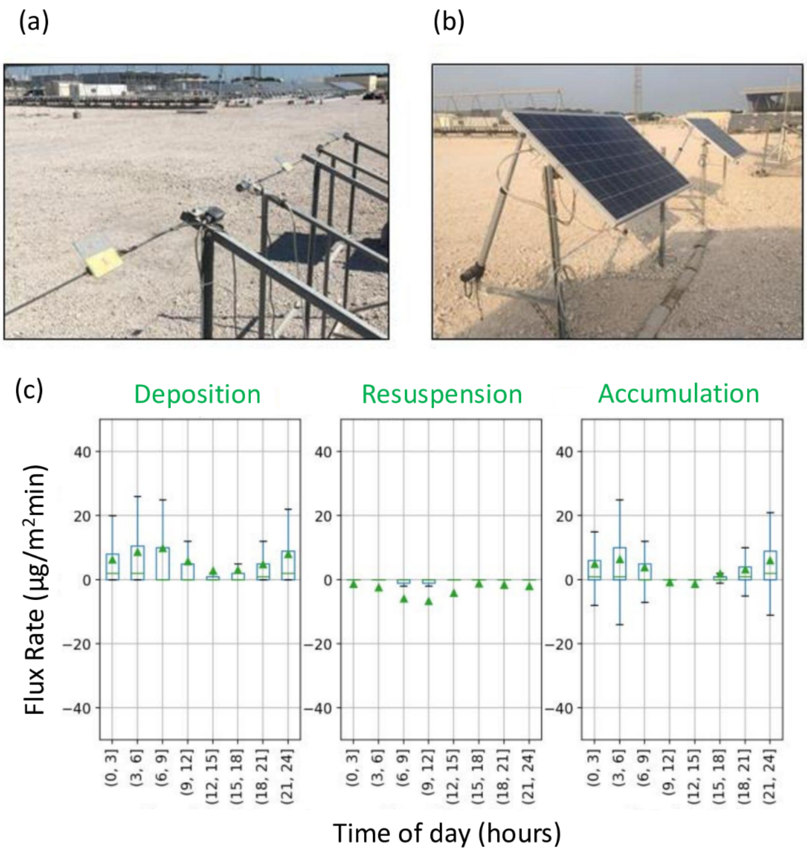

Figure 22. (**a**) 10 cm × 10 cm glass coupons were mounted on two 360° rotatable 1-axis trackers (left and middle of picture) and one fixed-tilt stand (right). The axes were aligned East-West; as pictured all coupons are tilted South (**b**) Two trackers with full-size modules were built, to validate results obtained from 10 cm coupons (**c**) Flux rate of dust to (positive values) or from (negative values) a horizontal glass coupon vs. time of day in Doha, Qatar. Adapted from ref. [126].

8. Effect of Soiling on Bifacial PV Modules

It was reported that bifacial PV harvests sunlight from both sides of the module, which can significantly increase the energy yield per module by up to 30% compared to monofacial and therefore, the levelized cost of energy (LCOE). This bifacial ability is however subjected to many parameters including the height of the module, the distance between them, and the albedo. Studying the soiling effects in bifacial modules is critical since dust accumulation is one of the most impacting factors for PV power loss, and hence a relevant parameter to consider when designing the bifacial system.

Soiling on bifacial PV systems is a complex problem and requires an in-depth investigation of installation parameters: such as tilt angle, mounting height, and rear/front side dust deposition rates [127–138]. Vertical bifacial modules show great potential for negative soiling which can be employed as noise-barriers, building integrated systems, and for peak shaving of the power profile using east-west orientation [127–138]. In principle, all PV systems (bifacial or monofacial), experience a soiling effect; however, the effect on bifacial PV is less pronounced. This is primarily due to a smaller amount of dust exposure on the rear side of the module in tilted systems or due to the vertical installation practice of bifacial technology [138]. With the recent interest in bifacial PV installations, the impact of soiling on energy yield and LCOE has become the prime focus of the solar-energy community for accelerating its deployment [40,127–138].

To quantify the impact of vertical mounting of bifacial modules, Bhaduri and Kottantharayil [33] conducted energy loss experiments for three configurations: vertical bifacial (VB), latitude tilt bifacial (LB), and latitude tilt monofacial (LM) panels.

The experiments, conducted in Mumbai for 55.7% bifaciality factor, showed that vertical bifacial (VB) modules yield almost negligible soiling loss (0.027%/day) as shown in Figure 23a. On the contrary, latitude tilt bifacial (LB) resulted in a soiling loss of 0.39%/day loss and LM showed 0.40%/day as highlighted by the slope in Figure 23a. A similar work on the effect of tilt angle on a soiling deposition by Qasem et al. [1] also revealed that there was nine times less soiling on vertical modules than 30° tilted modules. For bifacial modules, the daily soiling rate was measured to be 0.236% whereas, for monofacial, it was 0.301%. Table 4 consolidates the results from bifacial/monofacial soling loss studies in the literature for comparison purposes.

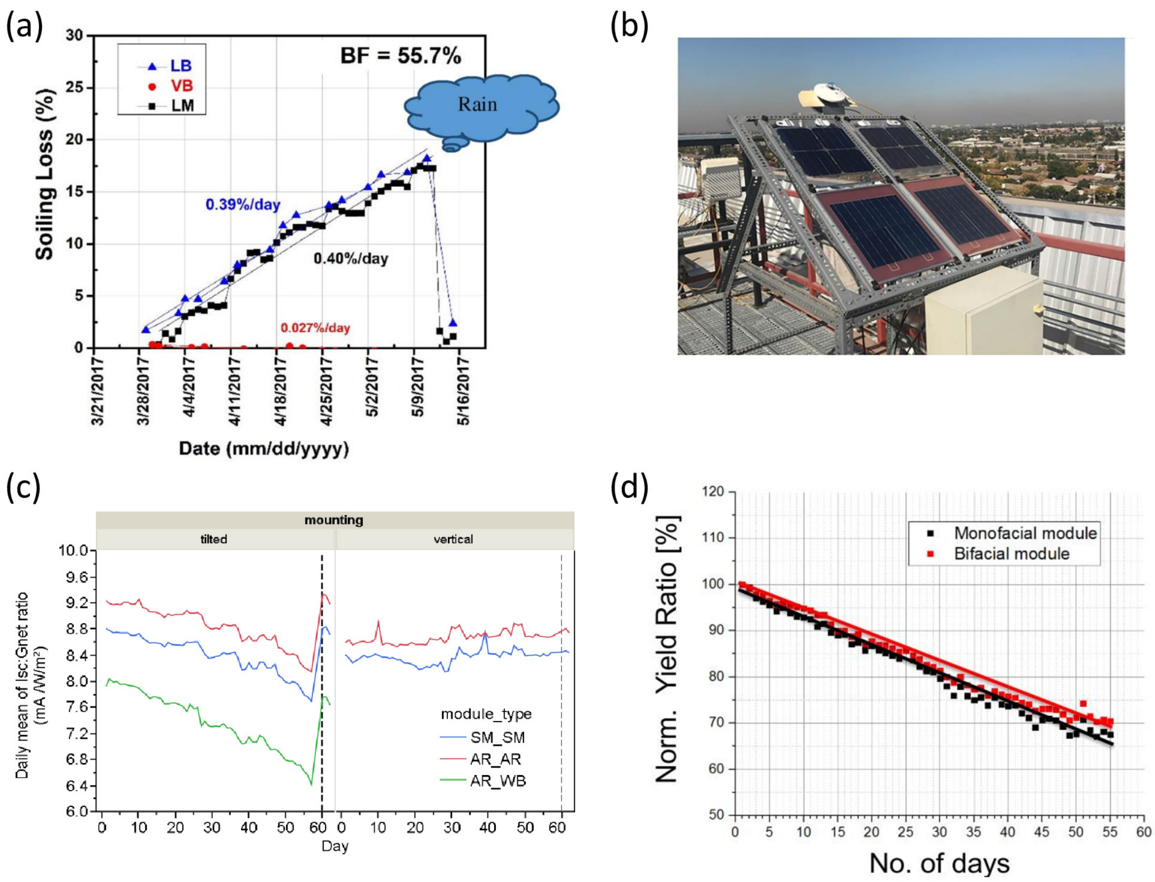

Figure 23. (**a**) Soiling loss experiments for three configurations: vertical bifacial (VB), latitude tilt bifacial (LB), and latitude tilt monofacial (LM) modules [127], (**b**) Monofacial and bifacial minimodules tested for soiling [128], (**c**) Soiling loss on monofacial and bifacial modules for tilted and vertical mounting using a ratio of short circuit current and global net irradiance [129]. Here, SM, AR, and WB denote different types of front/back sheets, and (**d**) Our calculations on the normalized yield ratio for bifacial and monofacial tilted modules in a desert climate.

Table 4. Summary of soiling loss studies for bifacial and monofacial modules.

Study Reference	PV Technology	Tilt Angle	Soiling Parameters
Ullah et al. [131]	Bifacial	30°	1.12% (daily soiling loss)
		Vertical	0.22% (daily soiling loss)
	Monofacial	30°	0.84% (daily soiling loss)
		Vertical	0.11% (daily soiling loss)
Bhaduri and Kottantharayil [133]	Bifacial	Vertical	0.027%/day
		Latitude Tilt	0.39%/day
	Monofacial	Latitude Tilt	0.40%/day
Qasem et al. [1]	Monofacial	Variable Tilt	9 times less soiling on vertical modules than 30° tilted modules
Luque, Antonanzas-Torres, and Escobar [134]	Bifacial	Latitude Tilt	0.236%/day (Total Soiling rate) 0.0394%/day (Rear Side Bifacial Soiling rate)
	Monofacial		0.301%/day (Soiling rate)
Rabanal-Arabach et al. [132]	Bifacial	Vertical	No notable soiling loss, ∼−0.0%
		Latitude Tilt	−12.5% (power loss due to dust)
	Monofacial	Latitude Tilt	−17.25% (power loss due to dust)
Dassler et al. [135]	Bifacial	22° Tilt	0.61%/day (Soiling rate)
	Monofacial		0.57%/day (Soiling rate)
Moehlecke et al. [138]	Monofacial and Bifacial	Latitude Tilt	Power degradation due to dust is similar for both technologies: 1–4%

9. Impact of Soiling on Energy Cost and Power Production

There is a clear competition between the cleaning cost and revenue losses originating from the soiling between the two cleaning events. To estimate the global impact and the associated cost of the soiling process with a descent accuracy, we have determined the optimum between these two competitive processes (i.e., soiling vs. cleaning) for the top 20 dominant PV and CSP markets. The associated dataset was compiled both from the relevant literature and exchanges with stakeholders. This study has included the soiling rates, cleaning costs, and simulated local energy yields, presented in Figure 24B–D, respectively. Furthermore, the optimum number of the cleaning cycles was computed every year from 2017 to 2018 for each country, by considering the installed PV capacity as reported and the local feed-in-tariffs (Figure 24E), in addition to the medium growth scenario for 2023 and the average electricity price of about 0.03 EUR/kWh [40]. Moreover, the overall soiling costs were determined as the summation of the costs of the optimized yearly cleaning and the leftover income losses (Figure 24F). According to the data analysis, in 2018, the global solar-power production reduction to the soiling is estimated to be at least 4%, occasioning a conservative estimated monetary loss of at least EUR 5 billion [40]. Please note that additional costs related to optimized cleaning schedules (for instance in residences) may account for about 30% of global installations and cleaning rooftops was about eight times more expensive than cleaning ground-mounted PV [40]. Moreover, collateral effects such as increases in loan rates could have an additional financial impact. Thus, by 2023, the worldwide yearly power production losses due to soiling issues may rise substantially to 7%, generating more than EUR 7 billion [40]. Please note that in some regions of the world, additional specific parameters including air quality could reduce anthropogenic sources of soiling, albeit air-quality policies usually operate over long timescales [40].

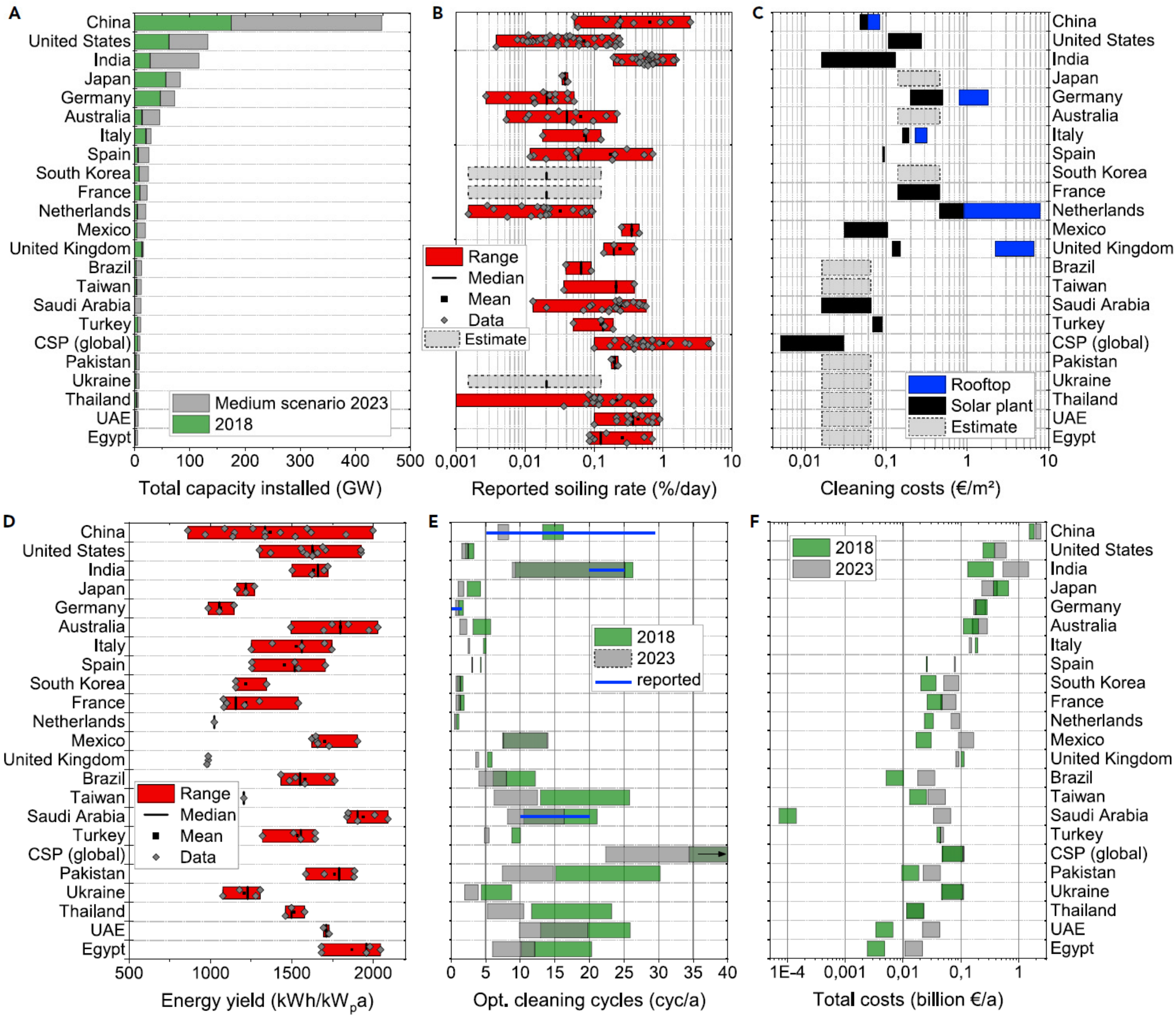

Figure 24. Effect of soiling on solar-power generation. (**A**) PV capacity operational by 2018 along with the medium expectation for 2023. (**B**) Associated soiling levels. (**C**) Cleaning costs related to the cleaning methods. (**D**) Standard energy yield in kWh/kWp for typical geographical spots. (**E**) An optimal number of yearly cleaning cycles (calculated: bars) and a real range of representative yearly cleaning cycles. Arrows show CSP. (**F**) The estimated monetary losses due to soiling. Adapted from ref. [40].

10. Renewable Energy and Soiling within the Gulf Cooperation Council (GCC) Context

We conclude this comprehensive review by highlighting the effort deployed by GCC countries regarding renewable energy and the specific issue of PV soiling. More globally, the deployment of large PV plants in dusty environments such as the Middle East, North Africa, India, China, South America, and the US put a finger on the serious concerns of the associated O&M costs [139–147]. Although the MENA region has the biggest PV generation potential in the world thanks to the abundant sunlight, it is also the stronghold of harsh climate factors, especially the events of dust storms and high particulate matter concentrations. Soiling considerably decreases the light transmitted to the PV solar cells and hence lowers the output PV power.

W. Al-Kouz et al. [148] proposed computational models based on optimized architectures of artificial neural network (ANN) and extreme learning machine (ELM), using field data, therefore investigating the impact of dust accumulation and ambient temperature on the PV performance (specifically the power conversion efficiency) in Jordan. The developed ELM model was found to forecast the PCE with an accuracy translated by an R2 of 91.4%, thus proposing an optimized cleaning frequency every two weeks. Lopez-Lorente and coworkers [149] focused their study on Cyprus, where an outdoor soiling test-bench was assessed for a continuous period of two years. A seasonally dependent soiling rate ranging from 0.039 to 0.535%/day was pointed out. Furthermore, using ML approaches and physical models, six different models of soiling were studied, in terms of their performance (i.e., accuracy) and their limitations. Physical models demonstrated better performance than ML ones, and the study provided useful information on the performance and limitations of the different soiling models applied in dry and arid climates. To predict the soiling losses occurring on PV systems, Micheli et al. [150] studied 102 different environmental and meteorological parameters where the performances have been compared over 20 soiling stations installed over the USA. Findings first demonstrated that the yearly average of the daily mean PM value was the best parameter for soiling predictors. Second, the precipitation pattern was also pointed out as a very relevant predictor parameter among the other meteorological factors. A preliminary investigation of two-variable regressions resulted in an R2 of 90%. In recent work, Micheli and coworkers [150] have also employed satellite-derived or ground-mounted PM data and demonstrated that this can lead to mapping the soiling, in different geographical locations, with high accuracy. In 2023, S. Bhaduri et al. [151] investigated the effect of raindrops, acidic water, UV radiation, and abrasion on the durability of anti-dust coatings. The rainy season was found to degrade these ADCs by 21 times compared to the non-rainy one. Interestingly, all coated samples showed lower coating life by 10 to 48 times when exposed to the impact of raindrops than those exposed to water immersion (water kept at a pH of 7), therefore indicating the impact of raindrops hitting, causing more damage than a simple water contact. These studies also highlighted the alternative chemistries of hydrophobic and hydrophilic coatings that may be effective in exhibiting long-term reliability.

Notwithstanding this inhospitable climate, various projects of utility-scale PV plants have been successfully commissioned. Table 5 shows the estimated renewable energy capacity in GCC by 2030. Figure 25b summarizes the current targets, where UAE is leading, followed by KSA. Figure 25d summarizes the renewable power planned additions by country. Looking forward, the state of Qatar has set a goal of attaining 20% of its energy from solar power by 2030 (one of the largest PV plants in the world), namely Al-Kharsaah, with 800 MWp already commissioned, and two more projects starting in 2023 will account for 875 MWp and will be delivered by end of 2024. Led by the UAE, the GCC region has about 7 GW in renewable power generation capacity. Solar PV remains the dominant technology with more than 75% share, followed by 10% of CSP and a 9% share for wind projects.

Table 5. Predicted renewable energy capacity in GCC countries by 2030. Adapted from ref. [152].

	Wind	PV Roof-Top	PV Utility Scale	CSP	Waste to Energy	Total	Source
				Capacity in 2030 (MW)			
Oman	1210	990	2420	770	110	5500	Target: 2.6 GW (~2025) + 0.6 GW every year up to 2030
Bahrain	20	70	520	70	20	700	IRENA expectation
Kuwait	200	1000	5800	1000	-	8000	Inputs from country
Qatar	-	150	2250	600	100	3100	IRENA expectation
UAE	300	4200	18,900	6000	600	30,000	Based on Masdar Institute/IRENA
KSA	3500	750	10,500	9500	750	25,000	Target: 9.5 GW (~2023) + 2 GW every year up to 2030

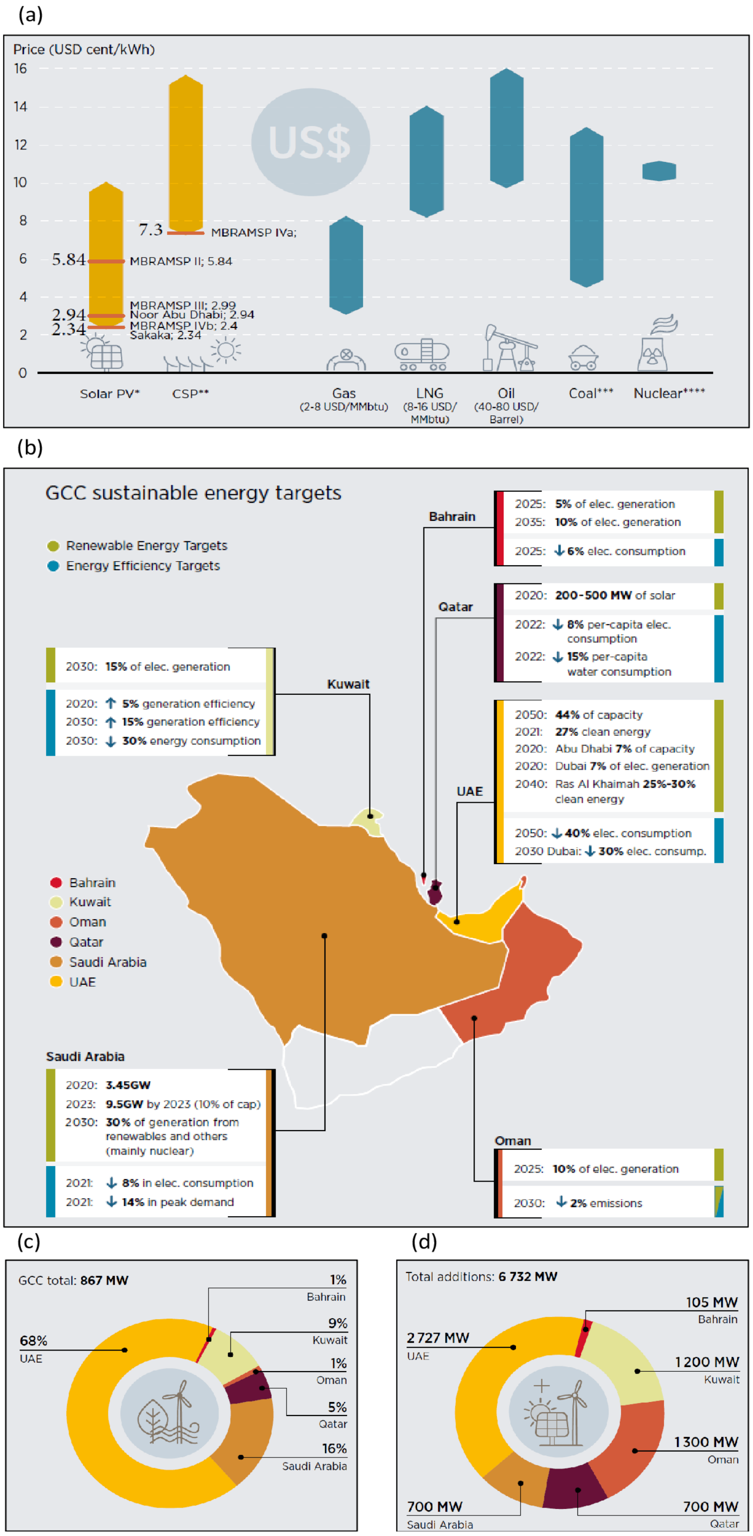

Figure 25. (**a**) Cost of electricity generation per selected technologies in the Golf region. * Low = price for 300 MW Sakaka solar PV; and High = a conservative assumption based on project data and expert opinion. ** Low = price for 700 MW in Dubai; and High = price for Morocco's Noor II. *** Low = price for the Hassyan Clean Coal Power Plant; and High = estimate for coal with CCS. **** Estimated range for nuclear power. (**b**) Targets of sustainable energy. (**c**) Already operational renewable energy capacity. (**d**) Renewable power planned additions by country. Reproduced with permission from ref. [152].

Towards such an effort, GCC is rapidly increasing the achievement of utility-scale PV plants, such as Noor Abu Dhabi (1.2 GW), Al Dhafra (2 GW), and Al-Kharsaah (800 MW) plants. We are now welcoming the new terawatt era of photovoltaic (PV) solar energy. The world's cumulative installed solar PV capacity grew by 22% to 940.0 GW by the end of 2021 claiming a 56% share of all renewable energies.

By May 2022, the installed capacity surpassed the milestone of 1 TW, led mainly by the deployment of large utility-scale solar plants. Although solar irradiance in the MENA region is among the highest in the world, soiling of solar collectors has been recognized as the main issue and the biggest detriment for solar-energy systems, decreasing their efficiency and increasing the cost of O&M.

Table 6 summarizes the main findings of the different sections developed during this review paper.

Table 6. Summary of the main findings.

Section	Main Findings/Recommendations	References
Impact of the soiling on solar radiation in Qatar	– Development of a national network of 13 high-quality solar radiation-monitoring stations across the state of Qatar. – Measuring the three components of solar radiation (direct, global, or total, and diffuse). – Study of atmospheric dust accumulation on sensor surfaces. [10–19] – Higher values of the integrated backscatter were seen in the summer season and during periods of dust storms indicating higher aerosol loads. – A clear relationship was pointed out relating to the hourly DNI clearness index. – AOD was well correlated with the particulate matter (PM) mass concentration using spectral ground measurements based on an MFRSR. – Solar radiation and dust accumulation effect on pyranometers in Qatar of the soling ratio quantified (loss per day between 0.3% and 0.5%) depending on the season.	[10–19]
Development of an in-house "outdoor soiling microscope"	– Development of an in-house device "outdoor soiling microscope" consisting of an adapted digital microscope, connected to a computer. A LED and a sheet of translucent paper were used to optimize the contrast of the dust particles. – Fast measurement (within a few seconds) of the droplet formation lifetime, including the onset and the vanishing of the condensation. Deposit dust particles that are above 10 μm^2 in size, measuring the Dust Particles removal. – Resolution of 2–3 pixels across, translated into the detection of particles of about 2–3 µm in diameter.	[20]
Field measurement of PV soiling by Mars™ and Dust IQ sensors	– Demonstration of field-test data measurements of the Mars™ and Dust IQ soiling sensors installed in different geographical locations in Qatar. – A high correlation between these sensors and a PV cell was demonstrated, especially during the cold season. – The mismatch of the soiling ratio measured from the two methods, namely the Mars™/DustIQ and the conventional clean/soiled reference cell pair method, was found to be less than 0.11%.	[21]
Understanding of the soiling properties in the desert environment	– The mean size might be considered at around 20 µm with a dominant spherical-like shape. – The dominant chemical composition of these desert dust particles are ($CaSO_4$), ($Ca_2Mg(SiO_7)$), wuestite (FeO), ($Al_2(SiO_4)O$), ($Mg_2(SiO_4)$), ($CaCO_3$) and (SiO_2). – The concentration of airborne dust was found to be a key factor in forecasting the soiling rates over different geographical locations over medium to long periods. – Three parameters were found to constitute the best PV soiling predictors, namely (i) the airborne dust concentration, (ii) the duration of the dry periods, and (iii) the rainfall frequency.	[22–53]

Table 6. *Cont.*

Section	Main Findings/Recommendations	References
Understanding of the soiling properties in the desert environment	– The adhesion forces between the flat glass surface and the dust particles were dominated by capillary forces in the presence of moisture, which may also prevent their resuspension by the wind. – van der Waals forces dominated the adhesion in the case of dry conditions, though gravity and electrostatic forces could be considered negligible. – Under windy conditions, when drag forces were present, rolling was the dominant detachment mechanism for particles. – A threshold of minimum rainfall water to clean the PV module was found to be dependent on the velocity of the droplet, dust composition, surface wettability, tilt angle, and dust adhesion forces, and varied from a daily minimum of 0.3 mm up to 20 mm, depending on the climate factors. – Temperature (T), relative humidity (RH), wind speed (WS), and the concentration of airborne dust, vary along the day as follows: T is lower during the night period, and higher during the daytime. PV module temperature is lower during the night period, and higher during the daytime. RH is higher during the night period, and lower during the day. WS is lower during the night period (around 3 m/s) and higher during the day (around 5 m/s). PM_{10} concentration has higher mean levels during the night period than during the day. – Surface properties play a critical role in the adhesion of the dust particle. – Typically, the nature of the adhesion forces is surface' property dependent, and has several forms: – Rough and smooth glass surface: van der Waals forces. – Hydrophobic and hydrophilic surface: capillary forces. – Charged particles: Electrostatic forces. – Gravity, when assuming the weight of the particle sphere. – Under high relative humidity, the adhesion process is governed by capillary force (98%), while during dry conditions, van der Waal force dominates. The main findings are detailed below: – Gravitational forces are negligible for particles size below 500 µm. – PV modules installed in OTF (Qatar) showed 5.1 K degrees below ambient temperature during the night. – The successive drying of the PV panel after the dew period increased dust particles' adhesion, by cementation, caking, and capillary aging. – Soiling occurs principally during the night period. – In ambient conditions, water droplets were formed on the surfaces of both glass and PTFE for 4 h, at nighttime. – Three processes govern the rate of dust accumulation on a given surface, namely: – "Deposition" refers to the particle in the atmosphere impacting the surface. – "Rebound" is when this particle is rapidly rebounding from this surface without adhering. – "Resuspension" occurs once this particle is resuspended by the wind. – Inclining the PV surface toward the airflow should promote the resuspension of particles. – Heating the PV module to mitigate dew depositions can effectively reduce the cementation process. – Condensation usually occurs before sunrise when the ambient temperature is higher than the module temperature due to radiative cooling, and when the relative humidity is high. – On days of dew prevalence, the soiling levels are recorded to be considerably higher than on dry days. – Active heat with reasonably high energy suggested a soil reduction of up to 65%. – No financial viability study of these warming strategies is yet available.	[22–53]

Table 6. *Cont.*

Section	Main Findings/Recommendations	References
Impact of PV soiling on PV performance	– Sedimentation is affected by gravity and is dependent on the tilt angle. – Inertial and resuspension are affected by wind and are dependent on both tilt angle and azimuth. – Deposition is more important than resuspension, and PV soiling is mainly controlled by sedimentation. – Soiling is more significant on moderately tilted surfaces rather than horizontal ones. – The maximum dust deposition in the OTF field test occurred at 45° facing the wind. – The maximum accumulation occurred at 22° away from the wind. – To decrease the soiling at night, a one-axis PV tracker should be stowed at a maximum tilt angle, facing the wind. – At 5 m/s wind speed, the average median diameter of the accumulated dust particles measured on the coupons was 20 µm. The accumulation of the dust particles was found to decrease with respect to WS and with respect to the tilt angle too. – For PV trackers that rotate commonly around ±45° or ±60°, a tangible reduction of dust accumulation could be achieved “for free,” especially during windy nights, by keeping the PV modules at a maximum tilt (ideally vertically) facing the wind. – Depending on the dominant meteorological conditions, the monthly average daily dust accumulation rate (DAR) was found to vary from 75 to 250 mg/m^2/day. – The lowest value of DAR is observed during June and is attributed to the high WS, and low RH% (although higher PM_{10} was observed during this month). – A DAR of 75 mg/m^2/day corresponded to a relative PV power loss of about 0.20%. – The average daily DAR generally follows the same pattern as the airborne PM_{10} concentration. – Higher DAR favors higher dust accumulation, and hence higher PV soiling. – The summer season (July–October) showed a decrease in the cleanness index (CI) by about 20% per month and this occurs consistently during only dry periods year after year. – Typically, for the bi-monthly cleaned panels, the associated PV power loss was about 15%/ month, with a clearly defined seasonal pattern. – During wet seasons, i.e., rainy periods, the CI reduction was limited to 10% due to cleaning triggered by the rain that prevents the accumulation of dust for more extended periods. – Wet season with higher rain rates such as in 2017 has shown a better CI (even close to unity) as compared, for example, to the same season in 2015. – Although the monthly PV soiling varied noticeably, the associated seasonal trends were more or less respected and the yearly change was less significant. – A threshold of a minimum of 3 mm rainfall was found to be the required value to fully clean the PV modules. – Dust storm days increase the annual average soiling rate by 23%.	[8,54–78]
Mitigation of PV soiling	– No cleaning process is currently universally recommended, as it depends on the availability of on-site resources, the economics, and the required frequency of cleaning. – Dry-cleaning-based technologies are applied in desert and arid environments where water sources are rare. – Wet-cleaning-based technologies are usually favored owing to their efficiency and the low potential for surface damage. – In the past few years, almost 100% of robotic cleaning was implemented in MW-scale PV projects. – The potential cost for applying automated cleaning is in the range of 2.4–8.2 EUR/m^2 with a possible soiling reduction of more than 95%.	[40,79–139]

Table 6. *Cont.*

Section	Main Findings/Recommendations	References
Mitigation of PV soiling	– The soiling level in the field declined as much as 80% using anti-soiling coatings when applied for a short time period. For extended times, typical anti-soiling efficiency is usually much weaker (for instance 20% –50%) and may grow worse than bare front cover depending on the quality of coating, regional weather, and deterioration level. – The long-term stability and reliability of passive coatings are difficult to foresee. – 41% soiling reduction was achieved on average by stowing vertically (90°) at night and a further 9% reduction by stowing upside-down (180°).	[40,79–139]
Effect of soiling on bifacial PV modules	– Soiling on bifacial PV systems depends on tilt angle, mounting height, and rear/front side dust deposition rates. – Vertical bifacial modules show great potential for free soiling (0.027%/day).	[1,127–138]
Impact of soiling on energy cost and power production	– The global solar-power production reduction to soiling is estimated to be at least 4% (in 2018), occasioning a conservative estimated monetary loss of at least EUR 5 billion. – By 2023, the worldwide yearly power production losses due to soiling issues may rise to 7%, generating more than EUR 7 billion economic.	[40,136]
Renewable Energy and soiling within the Gulf Cooperation Council (GCC) context	– MENA region has the biggest PV generation potential in the world thanks to the abundant sunlight. It is also the stronghold of harsh climate factors, especially the events of dust storms and high particulate matter concentrations. – Soiling considerably decreases the light transmitted to the PV solar cells and hence lowers the output PV power. – The state of Qatar has set a goal of attaining 20% of its energy from solar power by 2030. – One of the largest PV plants in the world, namely Al-Kharsaah, with 800 MWp is already commissioned. – Two more projects accounting for 875 MWp will be delivered by the end of 2024. – Led by the UAE, the GCC region has about 7 GW in renewable power generation capacity. – Solar PV remains the dominant technology with more than 75% share, followed by 10 % of CSP and a 9% share for wind projects.	[139–152]

11. Conclusions

The utilization of renewable energy in an intensive carbon-producing world has become a necessity to abate climate change and greenhouse gas emission threats. Among the different available options, solar energy is considered the most promising solution in sunny areas.

This comprehensive review summarizes the experience with key field-measurement findings and challenges in addressing soiling research obtained from the last decade of testing at the Outdoor Test Facility. PV soiling has been demonstrated to be a complex phenomenon, with a high degree of freedom and various interplayed factors, including environmental parameters, but also physicochemical, structural, and morphological properties of the dust particles.

Understanding, mitigating, and forecasting PV soiling is still in its infancy, and extensive research efforts are needed to solve this issue. At a short time scale, robotic cleaning, optimized cleaning schedules and forecasting of the soiling phenomenon based on atmospheric factors inputs are the most attractive options. PV cleaning machines are now available in the market. At a longer time scale, passive anti-soiling technologies, including anti-dust coatings, could decrease the frequency of the cleaning events and thus the associated O&M cost. This is supported by the promising results that were already obtained with textured films, including porous silica, metal oxides, and fluorides; however, the reliability of the passive anti-dust coatings should be assessed further towards their large-scale and commercial deployment.

Through the developed expertise gained from exposing PV panels to the harsh environment characterizing the desert of the state of Qatar, QEERI is offering a unique opportunity to test, assess and create innovative mitigation technologies that will help GCC arid regions and the world. The anti-soiling coating may serve as an efficient solution that complements the active cleaning process. Indeed, innovative solutions, cleaning concepts, and novel coatings are continually developed, addressing new functionalities, including self-healing, condensation run-off, and retrofit applications. Finally, QEERI has recently launched an ambitious project for the Dust Atlas, which revolves around the understanding, forecasting, and mitigation of environmental conditions, to address this issue from all possible angles. Fifteen (15) meteorological and dust-sensing stations have been installed over the state of Qatar to monitor the real-time PV soiling both geographically and seasonally.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ΔSR	Soiling ratio	MENA	Middle East and North Africa
ADM	Accumulated dust mass	IRENA	International Renewable Energy Agency
DS	Dust storms	QEERI	Qatar Environment and Energy Research Institute
CI	Cleanness index	QMD	Qatar Meteorological Department
AR	Antireflection	OTF	outdoor test facility
OPEX	Operational expenditure	GCC	Gulf Cooperation Council
PM	Particulate Matter	QSTP	Qatar Science & Technology Park
ASC	Anti-soiling coating	TAMUQ	Texas A&M University in Qatar
DAR	Dust accumulation rate	SEM	Scanning Electron Microscopy
AOD	Aerosol Optical Depth	OSM	Outdoor soiling microscope
O&M	Operation & maintenance	XRD	X-ray Diffraction
CFD	Computational Fluid Dynamics	STF	Solar Test Facility
CSP	Concentrated Solar Power	kW	Kilowatt
DNI	Direct Normal Irradiance	PV	Photovoltaic
GHI	Global Horizontal Irradiance	HSAT	Horizontal single-axis trackers
DHI	Diffuse Horizontal Irradiation	PERC	Passivated Emitter and Rear Cell
TNI	Total Normal Irradiance	TOPCon	Tunnel oxide passivated contact
POA	Plane of Array	RH	Relative humidity
LCOE	The levelized cost of energy	WS	Wind speed
LED	Light emitting diode	WD	Wind direction
MFRSR	Multi-filter rotating shadow band radiometer	T	Temperature
CAMS	Copernicus Atmosphere Monitoring Service	T%	Transmittance
PTFE	Polytetrafluoroethylene	IR	Infrared
PCM	Phase change Material	VB	Vertical bifacial
LM	Latitude tilt monofacial	LB	Latitude tilt bifacial

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