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Dust and PV Performance in Nigeria: A review

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ABSTRACT

The accumulation of dust on photovoltaic (PV) devices has an adverse impact by degrading their performance. In this work, a review of the effects of dust accumulation on PV module performance and measures to mitigate them have been provided. Energy losses from PV due to dust is an issue which cannot be ignored and can be an obstacle to achieving renewable energy targets in Nigeria. However, this paper presents a number of mitigation techniques which are available to maintain a certain level of performance. There is a need for further conduct comprehensive research on the effects of dust in all geopolitical regions in Nigeria to acquire data that can be used for designing the PV module system considering the most suitable technique in reducing or preventing the effects of soiling in each specific area.

1. Introduction

Rapid population growth has increased both world energy demand and consumption. The use of conventional fossil fuel generates a considerable percentage of toxic greenhouse gasses (GHG) which has a tremendous negative impact on our ecosystem. However, renewable energy from PV is an appropriate solution to this global energy crisis having the potential to reduce emissions of GHG from clean energy generation and is naturally replenishable. According to IRENE [1], solar PV energy generation had a global cumulative capacity of 390.62 GW and a recorded net addition of 93.65 GW in 2017, as shown in Fig. 1.

However, due to PV system exposure to outside conditions, the dust formation affects the performance of the technology. The term dust is defined as a general term for any substance or particles matter of that exist in the atmosphere with less than 500 μm diameter (10 times smaller than to the diameter of human hair) including but not limited to solid inorganic and organic particles such as soil particles, smoke (including factory smoke, vehicular smoke and firewood smoke) volcanic vapour, bacteria, pollen, fungi, microfibers and eroded limestones [3]. MSHA (Mine Safety and Health Administration) define dust as finely solid particles that initially exist in the atmosphere without any changes to their physical and chemical properties other than the breakage [3]. These particles exist in different sizes, volumes, chemical concentrations and shapes. In addition, particle types vary with geographical locations and their local activities. The term soiling refers to the process by which dirt, dust and contamination are deposited and accumulated on the surface of a solar PV module. This causes detrimental optical disturbance to the solar irradiance transmittance to the solar PV cell by reflecting, absorbing and scattering the rays leading to the degradation of overall performance efficiency. Dust accumulation is considered the third most significant factor that can influence the performance of a solar PV module after solar radiation and temperature. It is challenging to generalise the loss level caused by soiling on a PV module because the severity of soiling varies with geographical location and seasonal climatic conditions [4,5]. This presents a serious concern requiring rigorous research.

Most locations with high solar potential across the world are either arid or semi-arid, experiencing insufficient rain and pervasive dust which is considered one of the primary mechanisms that significantly affect the overall performance of PV devices [6]. Formation of dust on the PV module degrades the overall performance and reduces maximum yield during its expected period of operation. The degree of performance degradation varies according to a number of influencing factors, and these have prompted a significant amount of research interest over the last few decades. A number of review papers [3,6–13], have highlighted various approaches to the impact of dust on the performance of the PV module and various mitigation methods. In 2016, there was an increase of around 80% of the number of research and development papers related to soiling when compared to those conducted in 2015 [8]. In a continuation of this development, this review paper provides the reader with comprehensive information on PV module soiling based on the most current research to stimulate readers, the research community, PV system developers and installers on how dust can affect the PV

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List of abbreviations (including units and nomenclature)

A	Hamaker constant
ε	Epsilon - Dielectric constant
εo	Epsilon naught - Permittivity of free space
EDS	Electrodynamic Screens
g	Gravitaional acceleration
g/m^2	grams per square metre
GW	gigawatt
GHG	Green House Gasses
IRENE	International Renewable Energy Agency
ITD	Inter-Tropical Displacement
ITCZ	Inter-Tropical Convergence Zone
kWh/kWp	kilo Watt hour/kilo Watt power
ι	iota- Separation distance
LDH	Light Dust haze
m	meter
MENA	The Middle East & North Africa
mJ/m^{-2}	milliJoule per square metre
MJ/m^2	MegaJoule per square metre
μm	micrometre
MSHA	Mine Safety and Health Administration
θ	Theta – contact angle
p	Density
PM	Particulate Matter
PV	Photovoltaic
PTDF	Petroleum Technology Development Fund
R	radius
SALSA	Search, Appraisal, Synthesis, and Analysis
SHIP	Super Hydrophilic Plane
SHOP	Super Hydrophobic Plane
TDH	Thick Dust haze
TSP	Total Suspended Particles
TiO_2	Titanium dioxide
UAE	United Arab Emirates
UK	United Kingdom
VX	Visibility
W/m^2	Watts per square metre
γ	Gamma - Surface tension of water
ζ	Distance between flat surface and particle

performance in an area with high solar potential and less PV penetration such as Nigeria for further research. It is hoped that this will provide PV engineers with adequate knowledge for planning and designing an advanced system that can address the effect of dust on the technology considering specific locations due to differences of dust properties which is correlated to the environment and human activities. This study also aims to encourage the research community to focus the need for diversifying and extending studies on the effect of dust on PV to regions (developing countries such as Nigeria) where to date only limited research exists.

Grant and Booth [14] provided an analysis of 14 types of reviews and their associated methodologies, and each was analysed against SALSA (Search, Appraisal, Synthesis, and Analysis). Among the review types provided, state of the art review was adopted since it tends to address current issues and can assist the identification of areas that require further research. This research work used search engines such as Google, Google scholar, science direct database and Exeter learning environment for literature review sources. The keywords used were soiling, dust accumulation, dust formation, Nigeria, atmospheric dust, PV performance and mitigation techniques. A wide range of sources was considered including papers from the early 1980s to 2019.

This review paper describes soiling on a PV module considering dust as the main constituent. The next section of this paper describes dust and its properties, its sources and highlights provide details on the various soiling processes. Section 3 explains the impact of dust on a PV module with section 4 describing removal processes and available mitigation techniques for soiling. Section 5 highlights the particular sources of dust affecting power generation from PV in Nigeria.

2. Mechanism of soiling on PV

The mechanism of soiling on PV includes generation of dust particles from sources, entrained, transported (globally circulated), deposited, to PV module. Fig. 2 represents the entire soiling process starting from the generation process, which includes entrainment and transportation, to particle deposition on surfaces where some adhere, and others rebound or removed to become suspended again. This process is the entire life cycle of dust formation on PV and section two, and four explained all the phases from generation to resuspension phase.

2.1. Generation of dust

Dust is generated from desert storms, volcanic eruptions, industrial emissions, construction debris, highway activities, vehicle emissions,

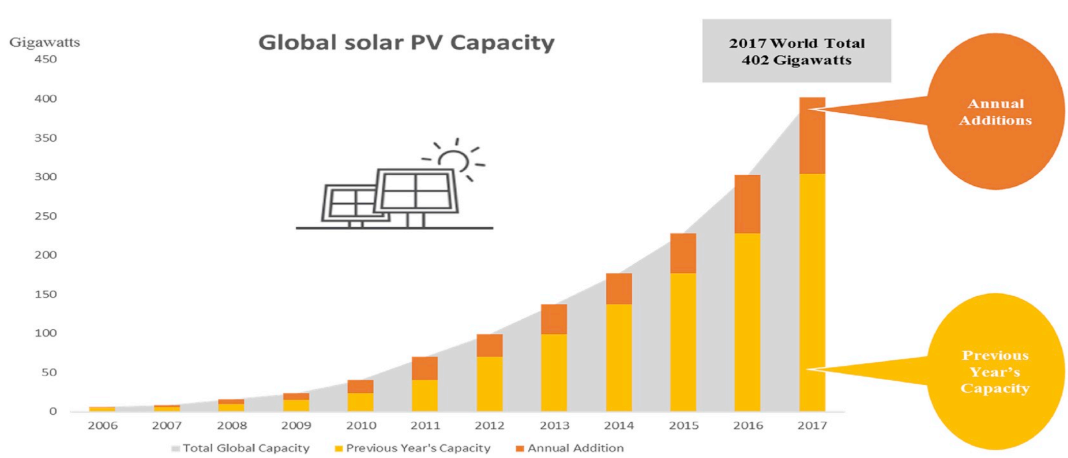

Fig. 1. Global solar PV capacity with annual increment (adapted from Ren 21 [2]).

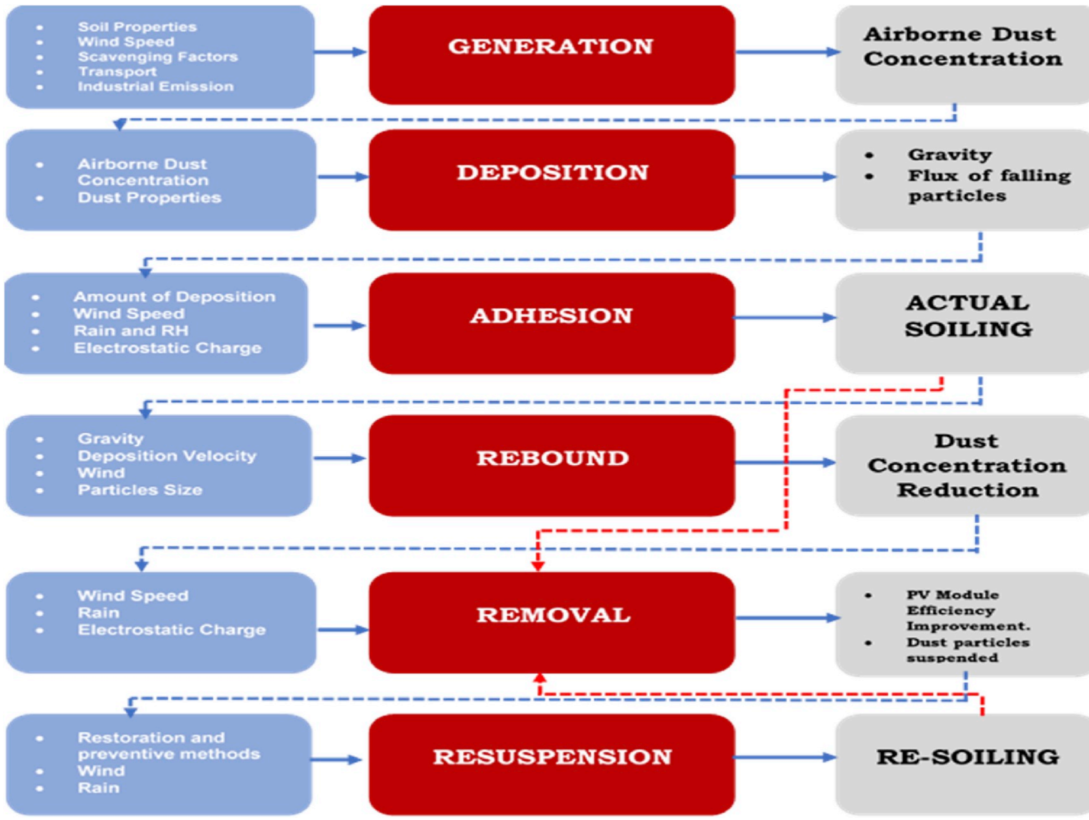

Fig. 2. Mechanics and phases of soiling.

microscopic organisms, pollen, plant material, dander (dead skin cells shed by animals) and other anthropogenic sources [3]. Some dust particles are generated and immediately deposited in the atmosphere, while other particles are initially generated and deposited to ground surface, then later entrained in the atmosphere due to anthropogenic or natural activities (such as wind and storms). Dust concentration in the atmosphere depends on the local topography, climatic condition, industrial activities and agricultural activities and varies across the world. Figs. 3–5 show the atmospheric dust concentration of various locations and their intensity indicating the MENA (the Middle East & North Africa) region as the location with the highest concentration.

Arabian Peninsula, Central Asia, North Africa (Saharan and Sub-Saharan Africa), South Africa, Western and Eastern China, Northern and Southern America and Australia [15–17] regions are the major sources of dust generations that contribute to global dust which originates from desert dust. However, these various regions do not have an equal active rate. According to Tanaka and Chiba [15], the Saharan dust generates about 58% of the total global dust emission and its

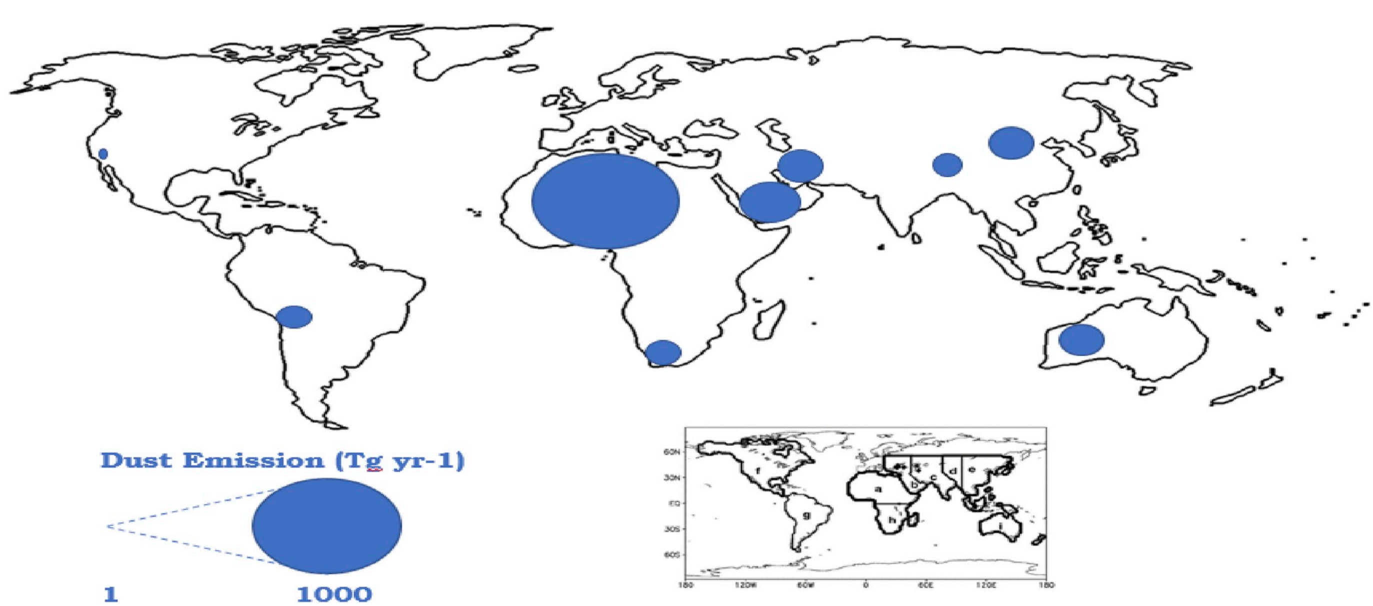

Fig. 3. Sources and Geographical locations/Borders of dust emissions (Adapted from Refs. [15,16]).

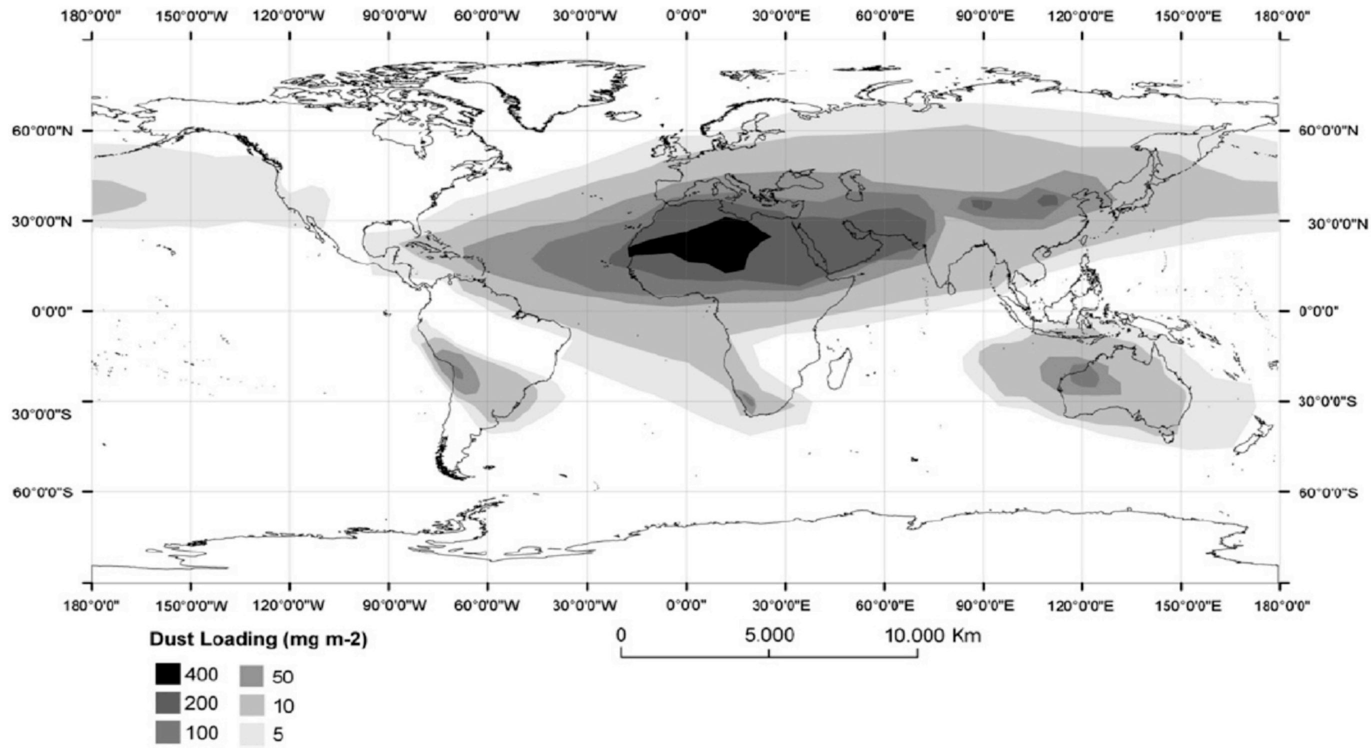

Fig. 4. Geographical distribution of dust loading in the atmosphere [15,16].

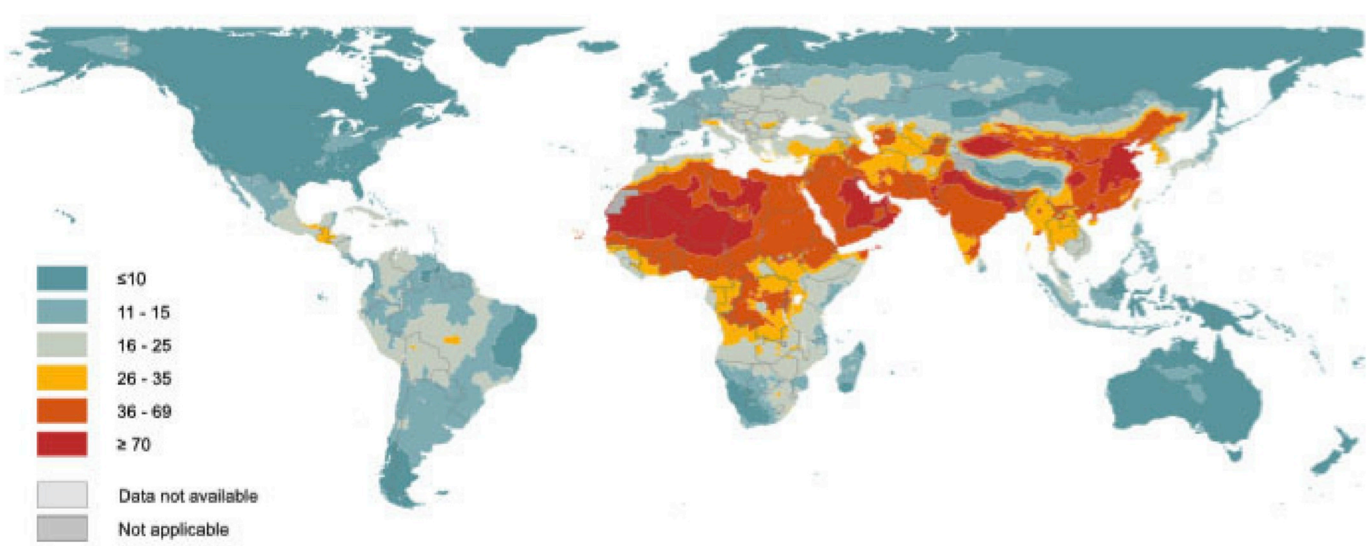

Fig. 5. Global map with fine dust particles concentrations [23].

entrained/load and contributes about 62% of the total dust in the troposphere as shown in Figs. 3 and 4. Nigeria is located within the biggest circle in Fig. 3, and the country is also positioned within 0°–30°N and 0°-30°E in Fig. 4 which shows it is within the region having the high loading of global atmospheric loading.

There is disagreement regarding the contribution of losses due to the size of the particle; however, particulate matter dimension between 0.1 μm and 1000 μm with the majority (about 50%) is common. Researchers [12,18,19] reported that the diameter varies from a diameter <20 μm and further classified the dust particles according to sizes:

- ➢ Deposited Particle Matter – this is any dust that drops from the atmosphere.
- ➢ TSP (Total Suspended Particles) – particle matter with the size of 50 μm or less.
- ➢ PM_{10} – particulate matter with the size of 10 μm or less.
- ➢ $PM_{2.5}$ – particulate matter with the size of 2.5 μm or less [19].

Transportation of dust by air in the atmosphere depends on the shape, size, surface properties and weight of particles [20,21]. Finer dust particles (with diameter <1 μm) have a greater tendency to uniformly cover the PV cell surface than the coarser (with diameter >5 μm) ones, causing a more significant decrease of solar radiation transmittance [21,22]. Fig. 5 highlights the various locations with a fine concentration in the world. These properties vary with locations across the globe because of climatic conditions, topography, agricultural, industrial activities, construction and other human activities. This causes determination of the actual dust composition to be fundamentally a location-based issue.

The threshold friction velocity and the vertical flux are the two major influencing factors for dust generation [18]. The generation phase includes the entrainment phase and the transport phase. In the entrainment phase, generated particles from erosion, industrial and agricultural emissions are deposited into the atmosphere due to wind flow. Dust is sometimes entrained in the atmosphere through the aerodynamic lift, saltation, through aggregate disintegration while others are emitted from various other sources and become suspended [18]. The entrainment activity is dependent on geographical location, climatic conditions and human activities [17]. After generation and being suspended in the atmosphere, dust can be transported over long distances by wind. Middleton [17] reported that dust from the Saharan desert has been transported through the troposphere over thousands of kilometres to Europe and Sub-Saharan Africa. In northeast Asia, dust is transported from the Gobi Desert to places like Beijing, Tokyo and Seoul. Dust movement is a transboundary activity that presents a significant challenge.

In summary, dust is generated from so many different sources. However, it has been highlighted as reported that the primary source of global dust is the desert dust in which West African and specifically northern Nigeria happens to be part of it. Figs. 3, Figs. 4 and 5 clearly show the location of Northern Nigeria and the entire country with proximity to the area of high dust generation and atmospheric loading, which present an alarming concern to the PV industry and its survival in the region. This section also highlights areas where a high concentration of dust particle is loaded in the atmosphere and transported around the world.

2.2. Deposition of dust on PV

This process involves the settlement of airborne dust particles on a surface. This phenomenon is strongly dependent on wind speed and particle matter [10,24,25]. The deposition rate of dust particles is higher if it is closer to the generation source and declines with distance [17]. The dust deposition on PV is categorised into three groups based on their transport mechanism [26], which are described below.

During the dry deposition process, airborne particles are transported to the PV surface in the absence of water content. In a dry weather condition, dust atoms adhere to the PV module surface because of the adhesive forces [18,26,27]. In a wet deposition, atmospheric dust is contaminated with various forms of precipitations such as fog, rain and snow [26]. These precipitations are the transport mechanism that deposits the particles on the surface of the PV module. The shadow deposition mechanism is described as an "intermediary" between the dry mechanism and the wet mechanism. This process is when clouds and fog containing water droplets are mixed with dusty air before deposition [26].

Dust accumulation or soiling is an unavoidable factor that affects solar PV module performance and is considered as one of the major factors after solar radiation and temperature. There are a number of factors influencing dust accumulation on a PV module, and these are represented in Fig. 6 and explained in the subsequent section of this paper.

2.2.1. Dust properties/morphology of dust

Soiling rate varies with dust property; dust particles that are less than 1 μm (finer dust particles) tend to settle and accumulate faster than those with a diameter greater than 5 μm (coarser dust particles) [21]. Similarly, particles with a larger diameter are easily affected by inertial and gravitational effect, while particles with a smaller diameter are affected by the inter-particles forces such as van der Waals forces, cohesive forces and electrostatic forces. In addition, particles with charged electrostatic properties tend to accumulate faster and settle more than dust particles with neutral electrostatic property due to coalescence [12].

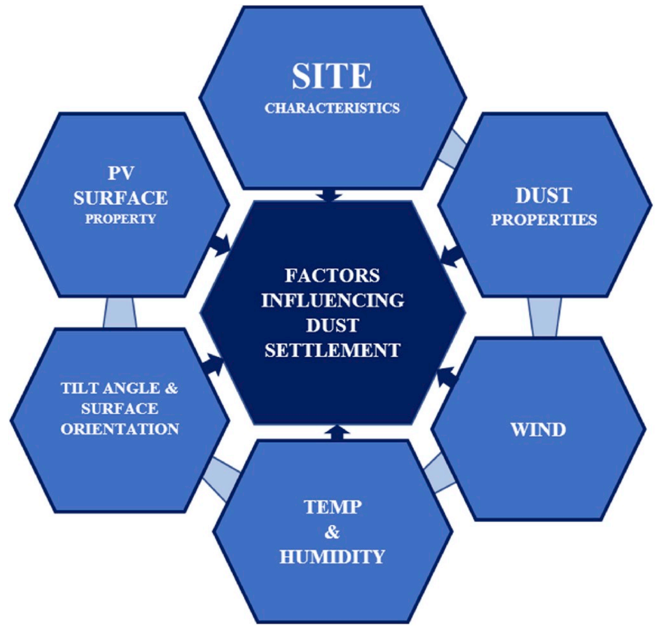

Fig. 6. Factors influencing dust accumulation on a PV (adapted from Refs. [21,28]).

Tanesab et al. [29], investigated the effect of dust on various PV devices (polycrystalline, monocrystalline and amorphous silicon) considering the dust morphologies as an influencing factor. Their result shows that large-sized dust samples are porous and allow more light to pass and dust with angular and diagonal shape have better optical property than particles with elliptical and spheroid shapes. Further stated that morphological properties tend to balance out and makeup transmittance value. Sisodia and Mathur [30] investigated the effect bird droppings on PV performance considering various tilt angle in correlation with the tendency of bird dropping pattern. Their result shows that optimal inclination angle 40° has the lowest bird dropping, and 0° has the highest deposition. Hachicha et al. [31] investigated the effect of morphology of dust samples on PV performance. Their result shows a linear relationship between dust density and normalised PV power with a reduction of 1.7% per g/m^2. Their result also shows a decrease of dust accumulation with an increase in tilt angle were 37.63% 14.11% and 10.95% with respect to 0°, 25°, and 45° tilt angles.

2.2.2. Surface property

The surface property of a PV module plays a significant role in influencing dust accumulation rate, and this rate varies with various surface fabrications. A surface with a coated layer has a lesser influence on dust settlement than that with an uncoated layer [21]. PV modules surface fabricated from tedlar, plastics and epoxy tend to have a higher dust accumulation rate when compared to surfaces made from glass [20, 32].

2.2.3. Local environment

Geographical site characteristics and its surrounding activities have a serious influence on dust accumulation on a PV module. Local site-specific factors such as human activities, natural topography and local development (urbanisation), vegetation and air pollution are factors that significantly influence dust accumulation. Cano et al. [33] stated that site characteristics are the main determinant of dust accumulation rate in a specific location concurrent with the local human and natural activities such as sandstorms, volcanic eruptions, dust haze from bush burning, transportation system, constructions and industries. The population density of an area also stimulates the dust entrainment and can influence the dust settlement [3].

Ghazi et al. [11] carried out a preliminary study of environmental particles on solar flat surfaces in the UK (United Kingdom) and concluded that dust accumulation is a complex phenomenon that varies according to location, environment and climate. Cano et al. [33] support this claim that tilt angle and surface orientation have a less significant influence on soiling rate on a PV module, claiming that the surrounding environmental condition and activities are the key influencing factors.

2.2.4. Wind

This is one of the main factors influencing dust accumulation. It is the mechanism that transports dust particles over thousands of kilometres and deposits it on a surface. Wind influences dust accumulation in a negative way and also in a positive way by removing and depositing dust. The dust properties and wind velocity determine the influence of wind over dust accumulation, which varies with location [21]. The rate of dust accumulation is reduced on a PV module due to the wind blowing when the module is positioned at a particular orientation and tilt angle [34]. Said et al. [35] reported that wind creates negative effects on the soiling because it promotes the transferring and spreading of dust particles in the atmosphere that leads to increased surface deposition. Goossens and Van Kerschaever [36] researched the effect of wind velocity and PV surface orientation in relation to dust accumulation. Their results show that dust accumulation increases with an increase in wind speed. Hegazy [34] investigated the dust effect on transmittance by measuring dust accumulation on glass coupons which were positioned at different tilt angles under various climate conditions in Egypt for one month and one year. The results show that degradation was dependent on the tilt angle where the maximum degradation was observed at horizontal position and minimum at the vertical position. The researcher recommended a weekly cleaning of the PV module to avoid performance degradation.

2.2.5. Temperature and relative humidity

Temperature and relative humidity are conditions that can significantly influence dust settlement on a PV module. Relative humidity dust accumulation when the temperature is high, and it is low, and this is a typical scenario in an arid or semi-arid location such as Nigeria which promotes easy transportation of dust particles by wind. Relative humidity usually becomes higher at night, thereby increasing the content of water vapour in the air and on contact with a surface at lower temperatures, it condenses and forms water droplets. The capillary force will then act to create adhesion of dust particles on a PV module surface [21].

Paudyal and Shakya [37] stated that relative humidity is a secondary factor that influences dust accumulation because it only plays a role in long-term soiling to cause adhesion, but the wind is considered as the main element that causes dust entrainment and deposition. Said et al. [35] stated that approximately 40%–80% relative humidity increases adhesion to 80%. This clearly shows that relative humidity promotes the cementation of dust particles which can be categorised as a secondary factor that influences dust accumulation. However, water droplets that condense from vapour on PV module surfaces can attract and hold dust. Adinoyi and Said [38] also stated that relative humidity promotes adhesion on module surfaces which would require vigorous cleaning to restore PV module performance.

Mekhilef et al. [39] investigated the effect of dust on a PV module considering humidity as the influencing factor. Their results show that atmospheric humidity has a significant influence on dust particle adhesion on a PV module which tends to degrade the efficiency of the technology. Touati et al. [40] experimented the effect of dust on PV module performance considering temperature and relative humidity as a factor that influences dust accumulation on a PV in Qatar for a period of two years. Their result shows that 50% degradation of power output was recorded due to an eight-month exposure without cleaning.

Wakin [41] conducted research on the effect of dust accumulation on a PV module for a period of 6 days without cleaning. Results show the degradation of 17% caused by soiling and further highlighted that during summer, degradation could reach 20% in 6 months. El-Nashar [42] investigated the seasonal effect of dust deposition on PV performance in the UAE (United Arab Emirates). Results show that glass transmittance reduction is higher during summer at approximately 10% and 6% during the winter. Results also show that 70% of efficiency degradation was recorded when the PV module was not clean over a period of one year. Research also confirmed that a single dust storm could reduce PV module output by about 20%. Zorrilla-Casanova et al. [43] studied solar radiation losses caused by dust accumulation on a PV module. Their results show that dust accumulation can reduce solar radiation by an average of 4% during rainy periods while during summer, a daily reduction of about 20% was recorded. Ghazi and Ip [19] investigated the dust effect on PV considering weather effect as the influencing factor in both outdoor and indoor experiments in Brighton, UK (United Kingdom). Their results from the laboratory (indoor) experiment show a reduction of 11% of light transmittance caused by fine dust particles, while results from the outdoor experiment show more severe degradation of the PV module performance which was related to weather conditions. Ramli et al. [44] investigated the dust effect on a PV module considering environmental conditions in Indonesia. Their results show a 10.8% reduction during the dry season, more than 40% during the rainy season with an average relative humidity of 76.32% and 45% when the average relative humidity is 60.45%.

2.2.6. Tilt angle and azimuthal orientation (PV installation design)

These are factors that have a significant influence on dust accumulation rate. The inertial dust deposition on a PV module is influenced by the tilt and azimuth angle of the PV module while the sedimentation is influenced by the surface's tilt angle. When considering surface orientation as a factor, dust accumulation is highest if the PV module surface is horizontally positioned and is moderate when tilted. When considering tilt angle as a factor, sedimentation is highest at a horizontal plane and reduces when tilted towards the vertical plane. The azimuth angle influence is depending on the wind, and degradation occurs similarly to that of tilt angle [10].

Hasan and Sayigh [45] investigated the effect of dust on transmittance using glass samples that were exposed to outdoor conditions in Kuwait for a period of 38 days. The sample was positioned at tilted angles of 0° (Horizontal position) 15°, 30°, 45°, and 60°, respectively. The results show the corresponding transmittance reductions of 64%, 48%, 38%, 30%, and 17%, respectively.

Elminir et al. [46] conducted research to investigate the dust effect on light transmittance using 100 glass samples. Their results show a reduction of transmittance with dust deposition and also show that deposition of dust varies with a tilt angle with 15.84 g/m^2 to 4.48 g/m^2 with a tilt angle from 0° to 90°, and the corresponding transmittance reduces approximately from 53% to approximately 12% respectively. Ghazi et al. [47] conducted an experiment that investigated the effect of dust on glass transmittance considering six different tilt angles (0°–90°) for a period of 3 months under the UK (United Kingdom) conditions. Their results show a low reduction of transmittance of about 5–6%. Cano et al. [33] conducted a study on the effect of dust on PV modules in Arizona State, focusing on tilt angle as an influencing factor. The result shows that about 2.02% degradation was observed when a PV module was positioned at 0° tilt angle, 1.05% reduction at 23° and 0.96% at 33° tilt angle respectively. Semaoui et al. [48] conducted a study on the effect of soiling PV module glazing, considering its optical transmittance in the desert area of Algeria. Modules were positioned at a tilted angle (32°) and results show a degradation of about 8%.

In summary, a generic list of factors influencing dust accumulation (site characteristics, dust properties, PV tilt angle, weather conditions and surface characteristics) on PV with each carefully elaborated with a relevant documented study. The effect of these factors is site-specific, and no documented evidence is showing any comprehensive research related to Nigeria.

2.3. Adhesion

Dust is initially deposited on the surface due to gravitational force; however, adhesion forces such as van der Waals forces, electrostatic forces and capillary forces are the active force that causes adhesion on a surface. The adhesion processes of these forces are described in Fig. 7 starting with the equation describing gravitational force where R is the radius of a dust particle, ρ is the density of the material and g is the gravitational acceleration constant [49]. Due to van der Waals force, small dry dust particles adhere over a dry surface [18]. This is considered the dominant force between a solid platform and a dry particle under dry ambient condition [49]. The van der Waals forces are always present between surface and particles and act within a short-range since they originate from two surfaces that are in contact with interacting dipoles [50]. The equation in Fig. 7 represents the dry a spherical dust particle on a flat surface where R is the radius, A is the Hamaker constant and Z is the distance between the flat surface and particle [49].

Capillary force is attributed to the moisture content in the air (RH-Relative Humidity) and on the surface. The capillary forces act when two wet bodies meet. Water vapour condenses in fine particles, thereby bridging the gap between the dust particles on a PV module surface resulting in adhesion [10]. Capillary force is more active if RH is below the saturation point, but once it reaches saturation (RH is 100%), then adhesion force will reduce. Capillary force combines two force components which the force due to pressure between water meniscus and air and the force due to surface tension [49]. The equation in Fig. 7 representing the capillary force describe adhesion of spherical dust particle on a flat surface where R is the radius, γ is the surface tension of water and θ is the contact angle between the substrate and the water [49].

Some dust particles have chemical compositions that cause them to be conductive or dielectric, and these properties usually control their interaction with the PV module surface. The electrostatic force causes adhesion when charges are present using two approaches; when the surface is wet and when particles are close to each other [18,19]. This electrostatic force can be either repulsive or attractive [50]. Dust particles tend to acquire electric charges in the atmosphere by colliding with one another and through other means and these charged particles tend to attract positive charge on the surface, which induces a coulomb force. On surface such low iron glass which is non-conductive, surface charges can come through tribo-electrification. Materials become charge when they have frictional contact with different material. The interaction is described in Fig. 7 where q is the charged particle, ε is the dielectric constant, εo is the permittivity of free space, l is the separation distance which is equal to 2 R [49].

A notable and catastrophic soiling mechanism which promotes adhesion using the types of force mentioned above (capillary force) is called cementation and is a process of adhesion originated from the dissolution of the soluble matter of wet deposited dust particles during condensation or dry particles on the wet surface, to form a strong solid bond with the surface upon drying [18,51]. This process usually occurs during evaporation and condensation [51] and possess severe consequence to PV performance. Dew formation is another phenomenon that occurs on the PV surface due to radiative cooling glass surface at night. This can serve as a mechanism that promotes the adhesion of particle on PV surfaces [50]. Particles are further rearranged, agglomerated and compacted together on surfaces to form particles caking which another severe form of cementation that can cause scattering and absorption effect of solar radiation leading to reduction of PV performance.

In summary, the main forces (van der Waals force, capillary force, electrostatic force and gravitational force) causing adhesion were discussed in this section with emphasis on the two most dominant (van der Waals force and capillary force) ones and the specific condition that triggers and promote their activities between dust particles and PV surfaces. All the adhesion forces are active almost everywhere, but the magnitude of their adhesion is determined by environmental condition and property of dust particles.

3. Impact of dust on PV modules

In 2017, the technology had an annual net addition installation of

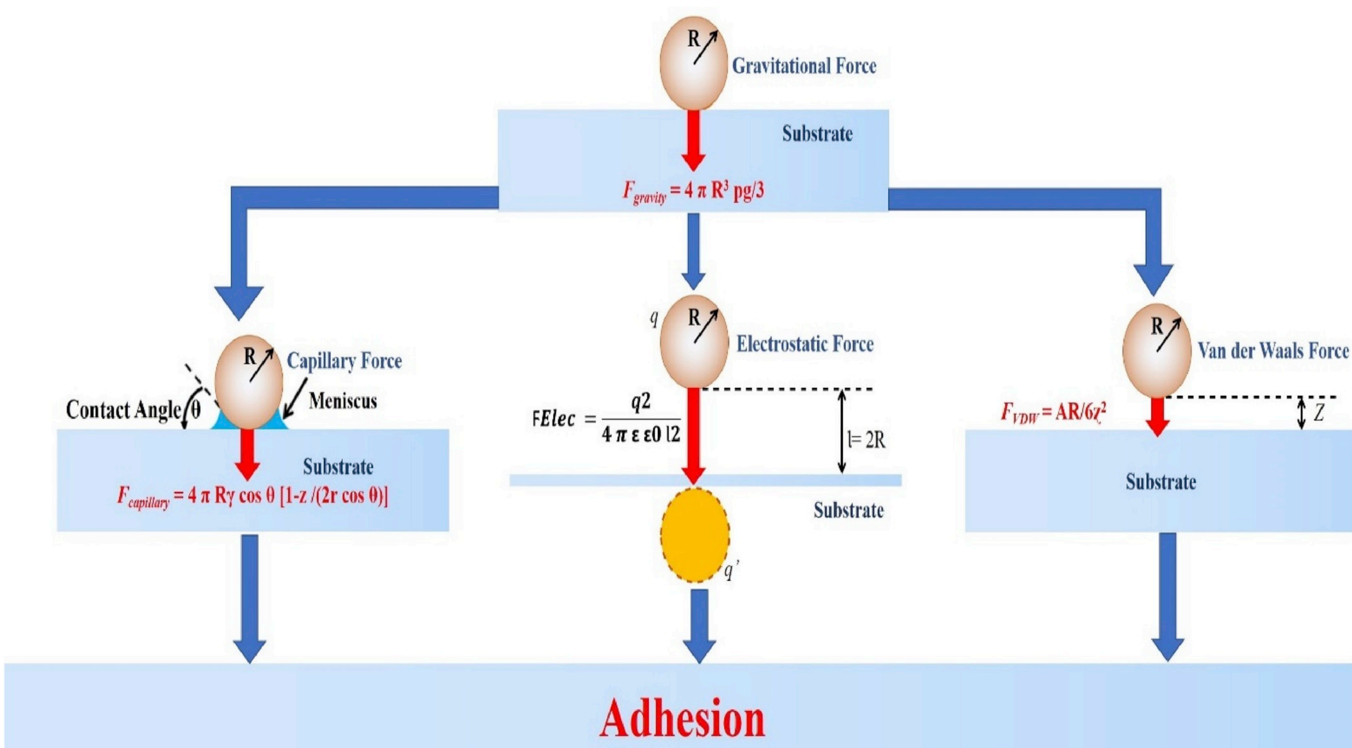

Fig. 7. Adhesion forces (adapted from Ref. [49]).

about 93.653 GW summing up to the global cumulative installation of 385.674 GW [1]. However, 243.715 GW was recorded as the cumulative generated capacity in the same year. This is due to factors such as dust that degrade the performance of the technology.

PV module performance is significantly affected by atmospheric and accumulated dust. A solar cell of a PV module cannot respond to wider spectrum sunlight because photons that have lower energy than the solar cells cannot be absorbed causing a material bandgap, as such 100% solar energy conversion cannot be achieved [52]. Therefore, efficiency degradation should be avoided wherever necessary, to achieve optimum performance.

As stated above/previously in this paper, dust is a global occurrence that negatively influences the PV module performance by scattering, absorbing reflecting and attenuating the solar radiation from reaching photovoltaic solar cells. Suspended dust in the atmosphere tends to reduce the performance of the PV module; however, this has a lesser effect than the dust that settles on the PV surface. These occurrences interplays to diffuse solar rays from reaching the solar cells, thus reducing the amount of light transmittance reaching the solar cells to perform efficiently and causing a substantial loss in energy production [53]. Dust accumulation tends to significantly degrade the performance of the PV module, and this has been established from a number of sources which are cited in the subsequent section of this paper.

3.1. Degradation of performance

The presence of atmospheric dust and the high level of deposition of dust on a PV module have a serious negative effect on the performance of PV solar cells. The degradation rate of PV's performance varies with dust particles, location and climatic condition. According to Zaihidee et al. [20], PV module performance degradation caused by dust is linear with dust deposition density. The rapid increase of solar PV technology installation across the globe and underperformance of the technology caused by dust has prompted considerable research interest. Salim et al. [54] conducted a study on the effect of dust on PV module performance for a period of eight months near Riyadh, Saudi Arabia, their results showing a 32% reduction of PV output. Tanesab et al. [55] conducted a study on the effect of dust on the performance of a PV module that has been exposed for almost two decades (18 years) without cleaning in Perth Australia, their results showing degradation of 8–12%. Sanusi [56] investigated the amorphous silicon PV module in southern Nigeria under dust haze (Harmattan season) for a period of three months without cleaning, which showed that a 20% degradation of PV performance. Klugmann-radziemska [57] investigated the PV power performance degradation in Poland, focusing on the current-voltage characteristic, chemical and physical characteristics of dust. The results showed a maximum loss of 0.8% per day of 37° tilted panels. The researcher also identified an average annual PV module performance degradation of 25.5% and 3% power losses. Sarver et al. [12] document a comprehensive review of the impact of dust accumulation on PV modules, highlighting that dust has a detrimental effect on PV performance. Similarly, Costa et al. [7] and Costa et al. [8] presented review papers with comprehensive listings and references for research that are related to dust accumulation on solar energy harvesting systems. In addition, Darwish et al. [3] presented a critical review that challenges the research questions that have been used in investigating the impact of dust accumulation on solar PV performance.

From an indoor experiment, it was found that coarser particles have a lesser impact, while finer particles have a more significant impact on solar cell efficiency [22]. An experiment performed on a rooftop in Athens showed a 19% degradation of PV module performance for red soil deposition, 10% for limestone and 6% for ash [58]. Mani and Pillai [28] investigated the effect of dust on PV module efficiency, focusing on the effect of the physical characteristics of dust particles. It was found that finer dust particles of about 2 mg/cm^2 reduced the PV output by about 30% while deposited coarser particles of about 8 mg/cm^2 reduced output by 10%. Sulaiman et al. [59] conducted a laboratory experiment using a light simulator to investigate the effect of dust on the performance of the PV module (mono-crystalline). Their results showed an 18% reduction in PV module performance when a dust sample was deposited on it. Kazem et al. [60] investigated the effect of dust (artificial) on PV modules using samples of dust (sand, ash, red soil, silica and calcium carbonate) of 5–10 g. It was documented that ash has the highest degradation effect on a PV module compared to the other dust particles. Ash reduced open-circuit voltage by 40% while sand reduced it by only 4%. Kazmerski et al. [5] investigated the interaction between dust particle adhesion on a PV module's surface, focusing on the chemical mechanism and morphology of dust particles accumulation. Their results show that adhesive force is highly dependent on the chemical bonding of dust particles.

Jiang et al. [61] conducted an experiment to investigate the effect of dust on three photovoltaic modules (monocrystalline silicon PV with a glass surface, polycrystalline silicon panel with an epoxy surface and thin-film amorphous silicon). The results show that efficiency degradation varies from 0% to 26% when the dust deposition density increases from 0 to 22 g/m^{-2}. Their results also show that polycrystalline exhibits greater efficiency degradation while monocrystalline PV module efficiency degradation was less compared to the amorphous silicon surface. In another similar research, Kalogirou et al. [32] reported the dust accumulation effect on three types of PV modules: monocrystalline, polycrystalline, and amorphous silicon. Their results show that polycrystalline and monocrystalline efficiency was significantly reduced compared to amorphous silicon PV modules. Urrejola et al. [62] investigated PV modules (monocrystalline, polycrystalline and thin-film) performance considering the effect of dust in Santiago Chile, for a period of two years. Their results show a daily degradation of PV module performance that lies between 0.13% and 0.56%. An annual degradation was also recorded with polycrystalline having 1.29%, 1.74% for thin-film system and monocrystalline having 2.77% reductions respectively. Alnaser et al. [63] conducted an out-door research where PV (monocrystalline) modules were exposed for 100 days without cleaning. They recorded a 10% degradation and they further recommended that PV modules should be cleaned at least once a month.

4. Removal of dust from PV

This is a detachment process that removes dust particles from the PV module surface [18]. Removal processes include artificial and natural, automated and self-cleaning, as shown in Fig. 8.

4.1. Natural removal

Rebound and resuspension are the two natural types of dust removal from PV surfaces. For the rebound process, the adhesion force is lesser than the dust particle's kinetic energy. Thus, the dust particle immediately bounces off from the PV module surface upon deposition and becomes re-suspended/re-entrained in the atmosphere [10]. Therefore, it becomes difficult to attract the particles and for them to become stacked on the surface. The rebound process is influenced by factors such as the size of particles and deposition velocity, PV module surface orientation, surface roughness, surface moisture, relative humidity and wind.

This is the resuspension of dust particles into the atmosphere after detachment from the surface of a PV module. This process is divided into two approaches; the energy re-suspension approach and the force re-suspension approach. The former occurs when adhesion tends to break due to sufficient energy from vibration or rocking, and the latter occurs when the aerodynamic force is higher than adhesion forces [10]. Particles are detached through lift-off motion, sliding and rolling. The amount of particle re-suspension is the function of the velocity flow. Wind speed plays a vital role in dust particle re-suspension. The dust particles size is another factor that promotes re-suspension, where a large sizeable particle is proportional to re-suspension force while the

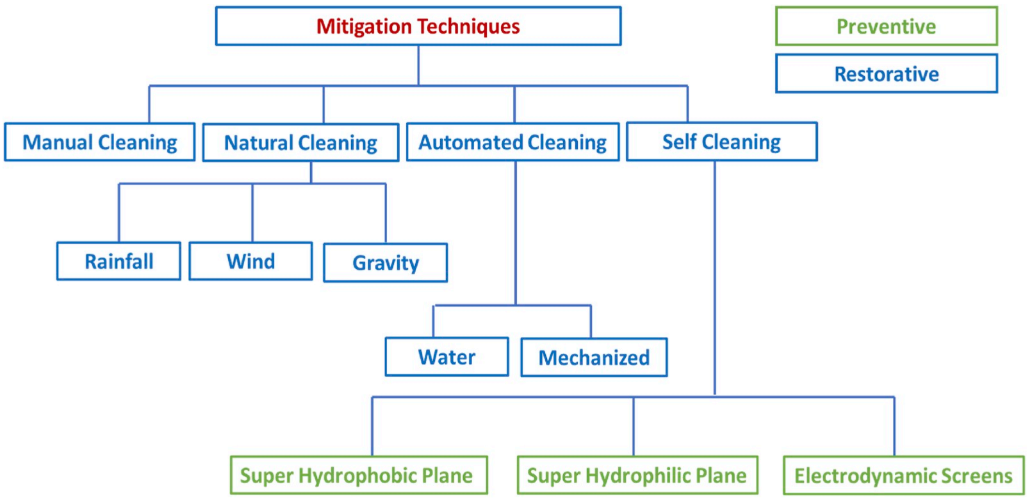

Fig. 8. Mitigation techniques.

adhesion force is linear to small dust particles [10]. This makes small particles immune to removal due to wind, while large particles are easily removed and re-suspended into the atmosphere by wind [10].

4.2. Cleaning

4.2.1. Natural cleaning

Rainfall, wind and gravity are the natural cleaning mitigation process of dust from a PV module [11] which are stacked on the surface by moisture due to the capillary force [64]. Rainfall is considered the most effective natural cleaning process and it improves efficiency by cleaning the PV module surface; however, the water droplets that remain on the PV surface tend to create adhesiveness on the surface [32]. Light rain has a negative impact because it collects airborne dust particles and deposits them on the surface, leaving sticky dirt patches which can cause a sudden decrease in PV module performance [65]. Rainfall is a natural phenomenon and as such cannot be relied on, most especially in arid and semi area areas.

High wind speed can partially clean a PV module surface, and this depends on factors such as wind direction and the tilt angle of a PV module [39]. This is also a natural occurrence similar to rain and as such cannot be depended upon. Low wind velocity also tends to drop suspended atmospheric dust particles on the PV module, which can cause degradation of its performance.

4.2.2. Water-based cleaning

This is an effective and the most widely used method of mitigating dust effect on a PV module. The pressurised water is used in cleaning the surface, and sometimes cleansing solutions such as detergent are also added to improve cleaning efficiency. This is considered one of the most efficient approaches. However, some areas such as arid and semi-arid locations with high solar energy potential have the problem of water scarcity, as the use of pressurised pumping machines can lead to the loss of a large quantity of water. The use of water in cleaning an electricity generating component also tends to cause thermal shocking. However, appropriate planning and timing of cleaning can resolve this problem [21,64].

4.2.3. Manual cleaning

This is the analogue traditional strategy used in cleaning a PV module, a similar approach to the one used in cleaning windows and glasses. Brushes and rags are used in scrubbing and washing the module surface to restore the cleanliness of the PV module surface. It is also efficient in removing cementations and hard soiling. However, since brushes and other materials are directly used on the PV module surfaces, there a (strong) likelihood of an abrasive effect. This method is also considered as an expensive approach as it requires other additional equipment for cleaning and is labour intensive [21,64].

4.2.4. Mechanised cleaning

This is the automated approach using a number of techniques for cleaning the surfaces of the PV module including mechanical wiping, mechanical brushing, blowing, vibrating/shaking and robotic cleaning. This method eliminates labour intensity by deploying automation. The vibration technique uses the piezoelectric effect to create ultrasound vibration that cleans the PV module surface. The use of this technique can restore about 95% of the power efficiency of a solar PV module [66]. Wiping and brushing techniques use the electromechanical approach, which consists of a programmable logic controller and a microprocessor to operate the wiper and brushes to move on the PV surface [11]. The robotic cleaning operation is similar to the one used in wiper and brushes techniques. Blowing employs the use of an air nozzle with a vortex generator attached to a brush or wiper to rotate across the PV surface [12].

These approaches require a considerable amount of energy and are relatively expensive because of the initial cost of devices and their maintenance. The cleaning efficiency of the technologies is still uncertain as some dust requires a thorough cleaning [21,64].

4.3. Self-cleaning coating

4.3.1. Super hydrophobic plane (SHOP)

This is a preventive approach using a self-cleaning concept that utilises a chemical or screen layer that requires no energy to repulse dust particles back to the atmosphere using the lotus effect. This self-cleaning technology has a surface with low wettability which has the capability of preventing water droplets from stacking on the PV surface assisting the removal of soiling with rainfall to improve cleanliness and increase efficiency [21]. However, the technology's lifespan is short, and it can easily break when exposed to high-level ultraviolet radiation. The use of this technology in solving the soiling problem remains unconfirmed [11,64].

4.3.2. Super hydrophilic plane (SHIP)

This is another preventive approach with a self-cleaning technique. The term hydrophilic expresses the diffusion of water on a surface. It is the exact opposite of hydrophobicity, where this Hydrophilicity attracts water, the other repels it. This technology used nano-pattern fabrication and was developed using TiO_2 (Titanium dioxide), which has been described as a low cost, high light transmittance, non-toxicity, chemically stable and highly durable material. However, it causes more soiling when the surface coating begins to deteriorate due to prolonged exposure to ultraviolet rays and requires washing and drying after rainfall [21,64].

4.3.3. Electrodynamic screens (EDS)

This is a preventive approach where the electrodynamic screen is placed on top of the PV module to prevent dust deposition by repelling it using an electrostatic field. It operates in dry ambient conditions with the capacity of detaching and restoring over 90% of PV module performance in 2 min [21]. However, it has been reported that it is not efficient in mitigating cementation and small dust particles [21]. The device also requires a high voltage of supply of electricity to generate the electric field on the PV module surface as such, reducing the capacity of generation by 15% [21,64].

In summary, the notable reported mitigation techniques were highlighted and discussed in this section. However, none of the technique implementation has been reported in Nigeria context for further analysis, and every site has an appropriate technique for it, considering all the factors such as sustainability, efficiency, cost implication analysis and energy loss analysis.

5. Nigerian context

Nigeria is a sub-Saharan country located in West Africa on the Gulf of Guinea with Niger and Chad to the North and Atlantic Ocean to the South. Its topography varies from semi-desert and savannah in the northern part to tropical forest and coastal swamp in the southern part. According to Nnaji et al. [67]; Ilenikhena and Ezemonye [68]; Ohunakin [69], Nigeria receives intensive sunshine, with an average of 6.25 h per day, ranging between 9.0 h in the far northern boundary to about 3.5 h in the coastal areas, meaning that Nigeria receives an average solar radiation of about 12.6 MJ/m^2/day at the southern coastal latitudes and about 25.2 MJ/m^2/day in the far northern part of the country, giving the mathematical average as 18.9 MJ/m^2/day [68–72]. This translates to an equivalent of 229.1667 W/m^2 in power terms [68–72]. The Global Solar Atlas [73] provided average PV power output potential of Northern Nigeria to be 4.8 kWh/kWp per day and Southern region to be 3.2 kWh/kWp with yearly totals 1753 kWh/kWp and 1168 kWh/kWp respectively. The atmosphere in the Northern part of Nigeria is affected by desert dust emanating from the Sahara in Northern Africa, Bodélé Depression, Bilma-Faya Largue in part of Chad and Niger Republics due to proximity, while the Southern part is mostly affected with the same dust and also soot that comes from oil exploration activities in the Niger Delta and offshore region when the wind the direction changes which is dependent on the positioning of ITD (Inter Tropical Displacement). This is caused by the Coriolis effects that direct the movement of the wind. Fig. 9 depicts some locations with high dust concentration in the atmosphere.

There are a number of sources of dust across the globe including the industrial pollution, mining, agricultural pollution, cosmic dust, volcanic, sea salt, desert dust and dust storms. A number of studies reported that Saharan desert dust is the largest source, with about 50%–58% of the total global dust [15–17]. According to Longueville et al. [16], sub-Saharan countries (West African) is the area of the world that is most affected by the dust from the Saharan region due to wind movement and proximity. The northeasterly winds usually blow off the Saharan dust and converge with the southwesterly wind to form the ITCZ (Inter Tropical Convergence Zone) in West Africa [74]. This has a tremendous effect on seasonal variability, which sometimes causes an influx of a high concentration of dust in the air around the region. Doherty et al. [74] stated that the ITCZ main mechanism drives the regional climate in West Africa because it plays a significant role in controlling wind direction. Middleton [17] further supported this claim by stating that the long-range transportation of desert dust mainly depends on the path of wind that differentiates seasonal variations. This high concentration of dry dust in the air that is being transported by wind from the Sahara through West Africa to the Gulf of Guinea is called the Harmattan season, which usually from November to March. Meindinyo et al. [75] describe Harmattan as a strong, hot, dry and dusty northeasterly trade wind that emanates from the Sahara and blow across West Africa.

The Harmattan season is associated with a deterioration of which visibility is due to the high concentration of dust particles (natural and anthropogenic sources) in the atmosphere. The visibility can drop to less than 1000 m, and Harmattan dust is categorised as TDH (Thick Dust Haze) which is when visibility $\leq$ 1000 m (VX $\leq$ 1000 m), and LDH (Light Dust haze) when visibility range from $>$1000 m to $\leq$ 5000 m [76]. Dust pollution with a reduce visibility below 1000 m is also considered as dust [77]. This season lasts for six months in Nigeria, and as such, can affect the performance of the PV system in the country. The quantity of dust in the air is higher in the northern areas and reduces when moving towards the south [16]. The dust particles vary and therefore, optical properties would also vary. The difference in the optical properties of dust depends on the regions and the distance from the source since particles are added and released during the transport phase [15]. Some can be opaque and others translucent capable of causing reduction of light transmittance. Middleton [17] reported that dust could degrade the performance of PV from about 15% to 30% in moderate dust conditions and if cementation occurs, it can reach up to 100%.

This Saharan desert dust injection is mobilised by Bodélé low-level jet (North Easterly wind) which transports about 60% of the particles southward towards the Gulf of Guinea having highest effect on Northern Nigeria, 12% northward affecting the Northern African and Southern Europe and 28% goes west to the Equatorial North Atlantic [77,78]. The low-level wind continues to generate sandblasting and saltation across the region during the Harmattan season, causing dust outbreaks leading to attenuation of solar radiation [79]. The wind is most active in January [80]. The aerosol granulometry of Harmattan dust is dependent on the distance from the initiation region, wind velocity that decreases with distance (Southward), and an increase in the atmospheric humidity [77]. Aerosol optical thickness (AOT) can be greater than 5 at peak

Fig. 9. Dust from locations across Nigeria (Adapted from Ogbaje [70], Quora [71]).

period [79], and texturally, the Harmattan dust particle is classified as silt and abrasive, but other different particles such as heavy metals are injected by anthropogenic sources during the transport phase making it hazardous [81]. The average Thick Dust Haze (TDH) duration of the Harmattan season ranges from about six days in the dry northern part of Nigeria to about a half-day in the southern coastal region [77]. This is mainly attributed to proximity to the primary emission source.

Anuforom [77] reported that the shrinking of the Lake Chad basin due to drought is increasing the concentration of dust level in the troposphere during the Harmattan season. The high concentration of dust in the atmosphere has a negative impact on incoming solar radiation by causing absorbing and scattering effect on a significant fraction of solar radiation leading to radiative imbalance, optical and electrical properties modification and changes of microphysical properties of clouds [77,79].

Documented evidence shows that soil in Northern Nigeria is mostly attributed to Harmattan dust from Aeolian suspension and saltation deposition (dune sand) [82]. Structures such as Zaria and Funtua loessic in Northern Nigeria have particle texture that appears with morphological and mineral characteristic similar to the ones obtained from Harmattan dust while particles from Northern mantles are predominantly similar to particles from the dune sand [82,83]. The soil of the Southern part of the country is mainly attributed with high erosivity and can be easily entrained into the atmosphere by the wind; however, the region has enormous vegetation with low wind velocity [84]. The high possibility of soil erodibility and erosivity in Northern Nigeria is a potential source for dust entrainment, where a large volume of dust is injected into the troposphere influencing the changes in the global radiation budget by directly scattering and absorption of solar radiation reducing the photovoltaic effect reaching PV technology [80,85].

Nigeria is categorised as a developing country, and the level of air pollution in the country is expected to be low due to less industrial activities. However, the country is blessed with abundant mineral resources, leading to several legal and illegal mining activities across the country, causing massive injection of heavy metals and minerals into the atmosphere that can cause air pollution and other hazards [86]. Mining activities generally come with a substantial positive economic benefit; however, it is always having some consequence attached to it. The negative impact of mining-related to this study is the emission of heavy metals into the atmosphere, which can have absorbance and scattering effects of solar radiation. Olujimi et al. [87] reported a high rate of Geo-accumulation index, indicating mining site contamination in Northern Nigeria with a high-risk level of cancer for both adults and children. Large scale volume of dust is generated from various mining activities such as oil and gas, cement, quarry, other minerals mining in the country. These industries generate a significant amount of dust during the mining of raw materials and generate another large volume during the utilization phase.

The oil and gas industry in Nigeria generates the highest air pollution as it is the primary source of revenue for the country. Apart from oil spillage, illegal refineries are also generating unaccountable emission from the sector, Nigeria is the 6th largest natural gas flaring country with approximately 180 gas flaring sites generating toxic gases into the atmosphere [88]. According to Aigbedion and Iyayi [86], large endless burning flames are common sites in the oil-producing region in Nigeria, flaring of the enormous volume of gases that are very dangerous to the environment and the PV industry.

Nigeria has a good number of cement companies producing locally for domestic consumption. These companies obtained their primary raw materials locally from limestone mining in the country, thereby generating a large volume of dust daily at all stages [86]. Maina et al. [89] stated that dust generated during cement production in Nigeria is enormous, and some dust particles are also generated in various forms such as gas emission, leakages, clinker dust, raw mills and precipitator dust. Researchers also stated soil around the vicinity of the factory had been polluted with a large amount of heavy metals. In the cement industry, dust is mainly discharged into the atmosphere at various stages during the production process such as crushing, grinding, blending of materials by cranes, crushers, mills, rotary kiln and packaging processes [90,91]. These dust particles can be entrained and transported to cause a disturbance in the PV industry and other environmental and health issues.

The quarry industry is another sector generating a large volume of dust across the country due to high demand from the road and building construction industry. Particles are generated during stone crushing or production processes and entrained in the atmosphere, then transported by wind. According to Ugwu [92], quarry operation discharged a large amount of particles to the atmosphere ranging from 1.0 μm to 2.5 μm and transported over by wind over a significant distance.

Anthropogenic activities by using old or poorly maintained vehicles, petroleum and diesel generators, combustible biomass, forest fire, construction and demolitions are generating an enormous amount of dust in Nigeria [93]. An old or poorly maintained vehicle is another source of air pollution in Nigeria due to inadequate emission control contributing additional particles in the atmosphere. According to Akan et al. [94] and Kanu et al. [95], heavy metals containing toxic elements are discharged from poorly maintained vehicles all over the country as a result of oil leakages, fuel burning, tyres wearing, substantial exhaust particle emission and other mechanical non-exhaust emissions such as breaking and road abrasion. Ogunsola et al. [96] stated that vehicles emission causing air pollution in the country is most likely aggravated by poor vehicle and road maintenance and lack of emission management technologies such as catalytic converters. Fossil fuel generators and combustible biomass are widely used across the country to complement the electricity supply, thereby generating toxic gases to the atmosphere. These gases are entrained and transported over a long distance to cause environmental and health issues. Construction and demolition activities are happening all over the country and can generate an enormous amount of dust which in turns causes air pollution in Nigeria that generates both fine and coarse dust particles on-sites [97]. The wood industry generates an enormous amount of wood dust on daily in the country. The application of outdated tools and machines in processing wood leads to the generation of significant by-product, which is poorly controlled due to a poor working environment [98]. It is then entrained in the atmosphere and transported over a distance. This anthropogenic emission is mostly higher in large cities (such as Lagos, Port Harcourt, and Kano) with high population density across the country where emitted particles are visible, causing strong turbidity, lousy smell and eye irritation [99]. Suspension of toxic particles in the atmosphere with these characteristics will have a negative effect on the PV performance.

6. Discussion

This research paper has highlighted generic mechanics in which the soiling process occurs on the PV surface, and a section was provided to highlight the sources of dust in Nigeria. It is evident that dust is generated from various sources in the country. However, there is an excessive influx of dust from the Saharan dust causing severe impacts on PV performance in the country during the Harmattan period. Other sources of dust were described, which provide additional constituents to the atmospheric dust and promote further negative consequences of attenuating solar radiation by scattering and absorption of the rays. The wind is a factor that plays a vital role in triggering the advection activity where particles are made to entrain and are transported in the atmosphere. The reduction in wind speed with distance also promotes the deposition of dust on surfaces within the region. Particle adhesion in the country is dependent on the major active forces (electrostatic, van der Waals and capillary force) earlier highlighted. During the Harmattan season in the country, humidity is low, causing van der Waals force and electrostatic force to be very active, whereas the capillary force will be significantly less or completely inactive. However, the capillary force can be triggered by light rain, dew or high humidity at the beginning of the raining season due to the introduction of the South-Westerly wind (monsoon influx) caused by the migratory repositioning of the ITD [78, 79]. This will initially cause cementation due to the mixture of dust particles and light rain on a surface, causing the most considerable PV performance degradation, but the heavy rain will later arrive and serve as a mitigator to clean and restore the PV performance. However, enormous energy potential will be lost due to the low harvesting performance caused by soiling during the period.

Jaszczur et al. reported that PV modules are widely neglected and not adequately maintained with appropriate cleaning after installation, which leads to soiling, causing a deteriorating effect on the system performance. There is no documented evidence to date, but a large number of PV installation in the country (Nigeria) are not adequately maintained must especially the ones used for street lightning leading to system failure after a short period of time due to dust accumulation.

Many studies presented above extensively reported that dust formation on PV has a tremendous effect on the performance of the technology. However, only one study by Sanusi [56], was identified to have been conducted in Southern Nigeria using local parameters, and this study does not consider many significant factors influencing the dust formation on PV, and does not mention other research challenges. Dust formation is site-specific, and most of the studies presented in this paper were not conducted in Nigeria or focused on Nigerian conditions; however, this paper has provided both generic information on the effect of dust on PV performance and specific information on the region to guide further research. Investigating the major factors influencing dust formation on PV highlighted above can play a major role in understanding the soiling of PV for a particular location. This research can provide information on the appropriate mitigation techniques to be used in a particular region with high PV potential and low penetration.

A carefully documented section for dust mitigation technique was provided above to demonstrate various ways to prevent this serious problem (dust formation on PV) or restore the performance of the technology after dust accumulation. No evidence of implementation of any of the techniques in Nigeria was observed or reported in this studied due to lack of information. However, with or without the implementation of any of the technique, the natural cleaning technique (Rain, wind and gravity) will be active on the PV installation once exposed to outdoor condition across the country. This highlight a research gap to investigate the availability and efficiency of mitigation techniques used in the country to provide information to the research community and potential investors for future development.

A good number of research gaps were identified in this study, which is adequately addressed can provide the required information to promote the penetration of the technology to achieve the sustainable development goal seven which aim to ensure the provision of clean, modern, sustainable and reliable energy for all.

According to Ochei and Adenola [76], dust across Nigeria has a significant influence in reducing visibility due to the suspended elements in the troposphere, and this can lead to an absorption and scattering effect on solar rays. Similarly, if dust accumulates on a PV module platform, it can also reduce transmittance and promote reflectance. This can reduce the performance of the solar PV module. Dust movement and deposition is a natural phenomenon and cannot be eradicated but can be mitigated. A number of mitigation techniques were highlighted above, and there is a need to identify the particular dust properties in Nigeria and conduct an experiment to determine the appropriate mitigation techniques to be used in the country. Natural cleaning is considered ineffective during the dry season while manual cleaning might be cheaper due to the cost of labour in Nigeria, but all the other mentioned mitigation techniques are expensive and might lead to an increase in the cost of generating clean energy.

This dusty wind movement across countries has been influencing the formation and accumulation of dust particles on objects that are exposed to outdoor conditions. Solar PV is a technology that requires installation in outdoors and without any obstruction to receive maximum solar radiation, and this will make it prone to dust formation and accumulation which has a deteriorating effect on the performance of the technology. In order to promote PV system penetration and sustainability, PV research must identify the soiling status of various regions with high potential and design PV systems with efficient and sustainable dust mitigating capacity.

7. Conclusion

The performance of PV technology is facing a serious challenge caused by dust formation. This factor causes rapid degradation of a PV performance leading to considerable research interest across the world. In order to conduct a review of the effect of dust on PV systems in Nigeria, dust and its particles were described, and in addition, dust sources and mechanics of operations were discussed. The factors influencing the dust formation were also considered. The effects of dust on a PV module were highlighted, and a large number of related publications were presented. Various mitigation methods were also discussed in detailed. The review shows that dust is a factor that causes significant performance degradation of PV modules and its deposition on the technology is influenced by a number of factors. The review also shows that each of the current mitigation techniques has one or more disadvantages. An effective technique depends on the geographical location of interest and its particular climate conditions. However, to restore/maintain and improve PV module performance, periodic maintenance using one of the mitigation techniques must be adopted. The review also shows that Nigeria's atmosphere is polluted with dry dust that comes from the North African Saharan desert during the dry season and soot that comes from the oil exploration activities in the Niger-Delta region and offshore (Gulf of Guinea). It also highlighted that an enormous amount of additional dust is generated through anthropogenic activities across the country. These have a detrimental effect on the PV module performance. There is a need to conduct comprehensive research on the effect of dust accumulation on PV in all geographical regions across the world to acquire data that can be used for more efficient and effective planning of any future solar PV system.

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