Angular Dependencies of Soiling Loss on Photovoltaic Performance in Nigeria

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Nomenclature	
β	Tilt angle
°C	Degree centigrade
PVOUT _total	Total photovoltaic output and global tilted irradiation
m	Meter
mm	millimetre
km/h	Kilometre per hour
hrs	Hours
kWp	Kilowatt power
kWh/m^2	Kilo watt-hour per meter square
MWh/m^2	Mega watt-hour per meter square
T (λ)	Spectral transmittance
S(λ)	Relative spectral distribution of solar radiation
Δ	change
Δλ	Change in wavelength
Δτ	Change in relative transmittance
τ_x	Transmittance data of a coupon positioned at an angle relative to a horizontal surface
τ_{clean}	Transmittance data of a clean coupon
$\tau_{\beta(optimum)}$	Light transmittance of a coupon at the optimum angle of Abuja (13^O)
$\tau_{\beta(90)}$	Transmittance of a coupon that was vertically positioned (90^O to the horizontal plane)
$\tau_{\beta(45)}$	Transmittance of a coupon that was positioned in 45^O angles
PV_out	PV output
$PV\_out\ (\beta_{(90)})$	PV output with soiled coupon at vertical position (90^O)
$PV\_out\ (\beta_{(45)})$	PV output with soiled coupon at tilt position (45^O)
$PV\_out\ (\beta_{(optimum)})$	PV output with soiled coupon at optimum position (13^O)
$PV\_out\ (\beta_{(0)})$	PV output with soiled coupon at horizontal position (0^O)
$M_{(soiled\ coupon)}$	Weight of a soiled coupon,
$M_{(clean\ coupon)}$	Weight of coupon after cleaning
ρ_d	The surface density of coupon's accumulated dust
g/m^2	gram per metre square
g/mm^2	gram per millimetre square
nm	nanometre

Abbreviation	
3D	3 Dimension
ABS	Acrylonitrile Butadiene Styrene
BAPV	Building attached PV
BIPV	Building Integrated PV
DC	Direct current
DNI	Direct normal irradiation

ELEV	Terrain elevation
Eq.	Equation
Fig.	Figure
GHI	Global horizontal irradiation
GHI_{opta}	Global tilted irradiation at the optimum angle
NIR	Near Infra-Red
OPTA	Optimum tilt angle of the PV module
PV	Photovoltaic
SEM	Scanning electronic microscope
TEMP	Temperature
UTC	Coordinated universal time
UV	Ultraviolet
VIPV	Vehicle integrated PV
VIS	Visual
WAT	West African time

Abstract
Photovoltaic performance is significantly affected by soiling on its covering surface, which is strongly influenced by its tilt angle. This raises concern for the potential investor, policymakers, engineers, and local populace in regions where the soiling rate and its potential threats remain relatively unexplored. This study investigated the effect of dust accumulation on PV, considering the influence of tilt angle using a low-cost in-house developed soiling station exposed in a region with high solar energy potential, low PV penetration and high energy demand. Low iron glass coupons were exposed monthly, seasonally, and annually, each in three-position (horizontal, 45° tilt, and vertical plane). The result revealed that the highest reduction in transmittance was recorded on a horizontally positioned coupon with a significant decrease of about 88%. In comparison, the lowest transmittance reduction of an exposed coupon was recorded from a vertical position with about a 1% reduction. These transmittance reductions were further illustrated using PV power output reduction. Accumulated dust density on each coupon was recorded, with the lowest of about 0.2g/m^2 and the highest of 12.56 g/m^2. It was concluded that horizontally positioned coupons accumulated more dust and gradually decreased as the angle tilted towards the vertical position. This research work highlights cycles of high soiling in the region; the information could be used to predict soiling events that could provide maintenance guidance where optimum scheduling for preventing and restoring PV performance can be achieved.

Keywords: Soiling, Dust Accumulation, Tilt Angle, PV Performance, Dust Density

1. Introduction
Continuous depletion of fossil fuels and its consequent degradation of the atmosphere is causing the rapid deployment of clean energy harvesting technology worldwide. Photovoltaic (PV) technology has attracted a great deal of attention, being the fastest growing renewable energy source (Conceiç~ao et al., 2019; Xu et al., 2017). The penetration and acceptance of PV technology are also due to the resultant factor of over two decades of the extensive scientific and industrial devotional research effort that leads to the recent high gain in technological efficiency, which is critical for facing out fossil fuels and high drop of cost (REN21, 2019). The technology has enormous potential and wide application since it is easy to integrate, its resource is free and abundant, the price has remarkably declined over the years and has zero noise from operation (Xu et al., 2017: Chanchangi et al., 2020). However, PV performance strongly depends on the amount of solar radiation reaching the PV material, depending on the tilt angle and azimuthal orientation (Ullah et al., 2019). Dust accumulation on a PV system is an unavoidable phenomenon, and when it occurs on a PV covering material, it declines the transmittance significantly, which in turn result in a reduction of the power generation (Gholami et al., 2017). The extent of the effect of dust on PV performance is a function of the quality of accumulated dust, weather condition,

tilt angle, and surface orientation of the PV system in relation to the dominant wind direction (Elminir et al., 2006).

The incident radiation received by solar cells inside a PV module is lower than radiation falling on the extreme top of the module surface. The transmittance coefficient of the cover glass is critical for the performance of the device as the other factors such as tilt angle and orientation, and temperature (Gholami et al., 2017) since it has an influence on the influx of light that reaches the solar energy collectors (Elminir et al. 2006). The leading causes of this energy loss are PV surface materials (mainly low iron glass and acrylic plastic) and accumulated dust on the module surface (Cano et al., 2014). The first has a more negligible effect, which is always less than 9% transmittance reduction as reported by Chanchangi et al. (2020), while the second could cause a significant effect on the performance of the technology. In addition, Conceiç~ao et al. (2019) stated that soiling on PV decreases the actual radiance absorption by solar cells and, consequently, reduces the power output to as much as about 50% in some regions. Dust accumulation provides a shielding effect that causes a decrease in light transmittance, causing wastage of abundant solar energy resource. Determining local soiling would be significantly valuable for PV installation since it can increase energy generation and reduce cleaning task (Conceiç~ao et al., 2019). In certain situations, economic implications cause consideration of the trade-off between maintenance costs (cost of mitigating the dust) and energy production, thus, contributing to negligence or inadequate maintenance (Conceiç~ao et al. 2019; Tanesab et al. 2016). It is recommended that there is a need for continuous research on soiling in the target region with high solar energy potential and proposing large PV installation to avoid possible wastage and stabilise energy production that could improve penetration (Gholami et al. 2017; Abdolzadeh and Nikkhah (2019; Chanchangi et al. 2020a).

According to Asl-Soleimani et al. (2001), optimum tilt angle depends on several parameters: the type of application, maximisation of solar energy absorption, and site climatic conditions (such as sand storm, dust haze, snowfall, or Harmattan haze). The tilt angle is a crucial factor that determines the PV module's production capacity, whereas the deposition of dust is an unavoidable external variable to be considered (Xu et al., 2017). The optimum tilt angle of a location differs for various variables, such as time of use, geographic latitude, temperature, atmosphere and other ambient influences, such as dust and emissions. Several methods were employed to determine the optimum tilt angle of sites (Mani and Pillai, 2010) and Xu et al. (2017), where the calculation was based on local latitude alone. However, due to a number of factors mentioned above, it is challenging to deploy a mathematical model to determine a particular site's actual optimum tilt angle, but it can be estimated considering all the factors. Conceiç~ao et al. (2019) provided a model that makes it possible to calculate the optimum tilt angle for a soiled PV module since the inclusion of soiling provides an accurate result for different tilt angles being used in the absence of cleaning; rather than using an optimum tilt angle solely based on irradiance.

In recent times, solar energy systems are widely utilised in different forms and in different applications such as BIPV (Building Integrated PV), BAPV (Building attached/applied PV), VIPV (Vehicle integrated PV), solar farms (large grid), isolated solar micro, and mini-grid, car parking roofing and interior decoration (Ghosh 2020; Ghosh 2020a; Reddy et al., 2020). Some of these applications allow the positioning of PV absorbing surfaces at a location-specific optimum angle, while others do not allow due to their kind of application. According to Conceiç~ao et al. (2019), the angular losses coefficient has a dependency on the transmittance ratio. The positioning of PV module in an angle other than the site-specific optimum angle could lead to angular losses due to a reduction of solar irradiance reaching the solar energy collectors, causing an unwanted wastage of resources that could lead to a decrease in the performance of technology (Tanesab et al., 2018; Martin and Ruiz, 2001).

In reviewing the related studies, some highlights of related literature are as follows: Hasan and Sayigh (1992) studied the impact of dust on light transmittance using glass plates, which were subjected to environmental conditions in Kuwait for 38 days. The coupons were exposed at angles 0° (Horizontal position), 15°, 30°, 45° and 60°, respectively. The findings demonstrated corresponding light transmittance declines of 64%, 48%, 38%, 30%, and 17% respectively. Elminir et al. (2006) performed work to explore the impact of dust on transmittance using 100 glass plates. The findings reveal a decrease of transmittance with an increase in dust deposition and further demonstrate that the deposition of dust differs from 15.84 g/m^2 to 4.48 g/m^2 with tilt angle ranging from 0° to 90° and the resulting transmittance falls from approximately 53% to approximately 12%, respectively. Abdolzadeh and Nikkhah (2019) investigated dust accumulation and its impact on PV performance using several glasses exposed on wooden frames at multiple angles and directions in Iran for 12 months. Their findings show yield decreased between 2% and 16% during the 12 calendar months.

In similar research works, Ghazi et al. (2013) investigated the impact of dust on light transmittance, taking into account six different tilt angles (0°-90°) for three months under UK conditions. Their findings indicate small transmittance losses of around 5–6%. Cano et al. (2014) performed a study on the impact of dust on PV modules in Arizona State, concentrating on tilt angle as a factor of influence in developing soiling station with nine tilt angles (0°, 5°, 10°, 15°, 20°, 23°, 30°, 33°, 40°). The findings indicated that about 2.02% losses occurred when the PV module was positioned at 0°, 1.05% at 23°, and 0.96% at 33°, respectively. Hachicha et al. (2019) investigated the effect of dust on PV performance in Sharjah, UAE. Their result shows a linear relationship between the increase in dust density and reduction PV performance. Their result shows that dust accumulation is a function of tilt angle where a high accumulation of dust was recorded on a horizontal plane, and the accumulation reduces at a tilt angle of 25° and continues to reduce towards 45°. Semaoui et al. (2015) investigated the impact of soiling on the PV module glazing in the Algerian desert area. The modules were exposed at a tilt angle (32°), and the tests revealed a loss of around 8%.

Heydarabadi et al. (2017) studied the dust accumulation on a tilted PV panel considering a specific wind path. The findings revealed that the maximum deposition occurs at a tilt angle of 45° while the module faces southwards for larger particles (> 10μm) and 90° for particles smaller than 10μm. Figgis et al. (2019) investigated dust deposition and accumulation on coupons positioned in an axis perpendicular to wind in outdoor conditions and laboratories. Their outdoor result showed that maximum deposition occurred at angle 45°, but maximum accumulation occurred at 22° away from the incoming wind. It also shows that soiling can be easily reduced when PV modules are tilt towards maximum inflowing wind overnight for particle detachment.

Xu et al. (2017) analysed the influence of tilt angle in dust formation. They provided an inverse correlation between the tilt angle and dust deposition density. They also presented a method to calculate the optimal tilt angle of a soiled PV module to provide maximum power output, and this was validated using Matlab simulation. Qasem et al. (2019) investigated the effect of dust on spectral transmittance. Their results indicated that transmittance losses variations were higher around angle 30° with a non-uniformity of 4.4% compared to 0.2% around the 90° angles.

As reported earlier in this section, a number of researchers have investigated the PV tilt angle as an influencing factor in dust accumulation. However, the approach used in this research is scarce, and this provides improved information on how the tilt angle influences the accumulation of dust in areas with enormous solar energy potential and less penetration by considering a number of factors, such as reduced light transmittance, reduced PV energy generation, and mass of accumulated dust (deposition density) using a low-cost approach. There is a shortage of systematic approaches for exposure of coupons considering the weather and period variability to the consequences of dust deposition influence by tilt angle when reviewing relevant literature. Furthermore, many publications mentioned above presented time dependency results and may not be usable in the same region at a different time. The study investigated the influence of angular positioning in promoting soiling on PV considering transmittance coefficient losses, the mass of accumulated dust on surfaces, and potential PV output losses. However, since soiling is location-specific and PV technology is recently used for wider application varieties, it restricts it from being positioned at a specific angle. The study developed a soiling station that investigated dust accumulation considering monthly, seasonal, and annual formation that determines the effect of dust on PV performance at all tilt angles (0° – 90°) using interpolation as provided in the subsequent section.

To date, studies on the influence of tilt angle on dust accumulation for Nigeria is relatively unexplored, even though the country has enormous solar energy potential, and the government is making a considerable investment towards solar energy installation. The study has a novelty of presenting a low-cost approach that could determine the regional influence of tilt angle on PV soiling. It would resolve the threats of concern, such as the influence of angular position on PV soiling, which hinders the acceptance of technology in the region and presents a cost-effective and straightforward approach to determine angular soiling rates and their peak period. This will enable an optimal maintenance schedule and reduce operational cost to achieve a higher yield. Moreover, once PV performance yield could be sustained over its life cycle duration at an optimum rate, there is a high possibility of attracting potential investors and policymakers to finance PV projects, accelerating the technology's penetration and reducing greenhouse gas emissions. This paper contributes to the body of knowledge in the field of soiling on PV by providing a unique approach to determine the level of soiling at different angles, different period with their equivalent power losses and weight of accumulated dust which can serve as a guide to engineers for planning installation and determining the required optimum maintenance. It also provides a valuable substance that can motivate further research on prevention and restoration techniques to ensure optimum performance of PV technology is sustained. This work highlights the significance of the effect of soiling considering tilt angle as an influencing factor with the next section providing background and methodology used in the research and part 3 presents the results and discussion, while section 4 is the conclusion.

2. Methods

50mm x 50mm x 4mm low iron glass coupons were exposed to outside weather conditions in Abuja (09°03'N, 07°30' E), Nigeria's federal capital territory. Forty-five coupons were exposed in three groups (monthly, seasonal and annual) considering the period of exposure, where 36 coupons were used monthly, 6 for seasonal and 3 for annual. In addition, each group of coupons was placed in three positions; horizontal (0°), tilt angle (45°) and vertical (90°) using an in-house developed research jig shown in Fig. 1. The research jig design using solid works was fabricated using a Stratasys uPrint SE 3D printer with a P430XL ABS (Acrylonitrile Butadiene Styrene) material. This material was selected since its properties would not be transferred to the coupon surface during extreme weather conditions such as rainfall, high temperature, or dry-dusty wind. It has good thermal conductivity and remains stable at temperatures between -20°C to + 80°C. Samples were labelled on the 4mm part of the class with information such as location, period, and exposure position. All coupons were removed at the expiration of their exposure period and returned to the University of Exeter solar laboratory for detailed characterisation.

A crate was carefully designed using solid works and fabricated with the above-mentioned 3D printer, which was employed in transporting the samples. The crate was designed in two parts container (main container and the cover) to prevent movement, shaking, and breakage. Then the crate was placed in a sample Fisherbrand SureOne 02-707-411 container and filled with Eco-Flo biodegradable packing peanuts or bubble wrap packaging. The container is further wrapped with bubble packaging before shipping. On delivering the sample, each crate was examined to determine if the deposited sample was removed from the container by placing a plain white paper underneath the container before opening and when removing the samples. A very tiny quantity of samples was observed, and it would have any significant impact on the study's findings; as such, it was deliberately disregarded. Therefore, It was assumed that the formation pattern was not distorted during transport.

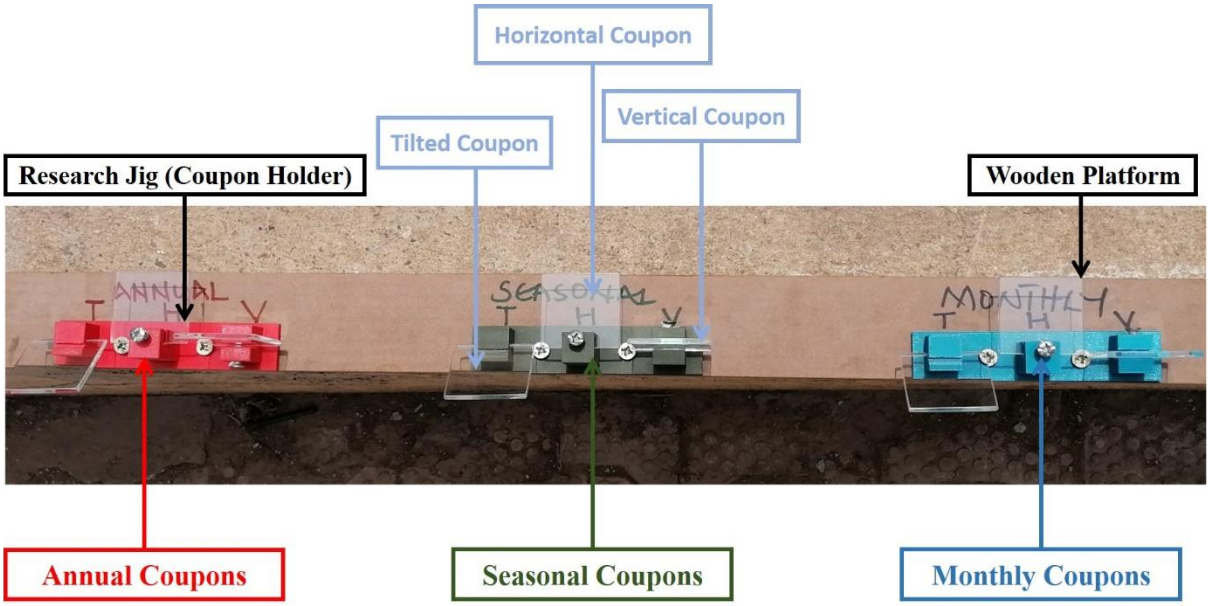

Fig. 1. Digital image of coupons and research jig installation

2.1 Site

Details about the site of exposure are documented in Table 1 below. This location was carefully selected because of its excessive energy demand (where 43.5% of the population does not have electricity access, and the remaining populace has an epileptic supply) and high interest in PV installation (World Bank Group, 2020).

Table 1. Site information (obtained from GSA, 2021)

Abuja Municipal (AMAC), Federal Capital Territory, Nigeria			
Coordinates	Latitude	08°59‘25"	North
	Longitude	07°21‘34"	East
Time zone	Time	UTC+01	Africa/Lagos [WAT]
Direct normal irradiation	DNI	1116	kWh/m^2
Global horizontal irradiation	GHI	1888	kWh/m^2
Diffuse horizontal irradiation	DIF	1052	kWh/m^2
Global tilted irradiation at the optimum angle	GTI opta	1927	kWh/m^2
The optimum tilt of PV modules	OPTA	13/180	°C
Air temperature	TEMP	27.3	°C
Terrain elevation	ELE	401	m
Maximum ambient temperature	Max a-temp	40	°C
Precipitation	Rain	561.5	mm

The average weather condition of Abuja was provided for analysis purpose of the dust accumulation on various coupons. Weather data were obtained from the World Weather Online (2020) Fig. 2 provides temperature, humidity, cloud, precipitation and wind during exposure.

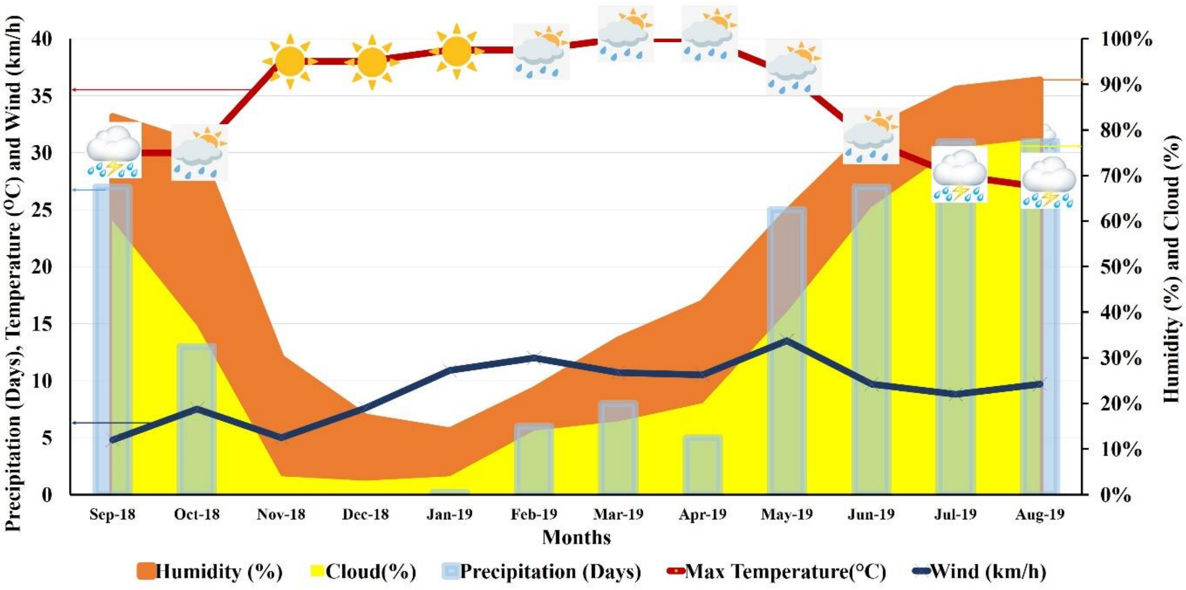

Fig. 2. Monthly weather condition variation for Abuja during the period when coupons were exposed.

2.2 Optical characterisation

Optical degradations of coupons were examined using the Perkin Elmer Lambda 1050 UV/VIS/NIR spectrophotometer. A clean coupon was initially tested to establish the optimal transmittance level of low iron glass, and subsequently, all the exposed coupons were also subjected to the same test where UV (Ultraviolet), VIS (Visual) and NIR (Near Infra-Red) transmittance level were measured ranging from 200 nm to 1200 nm wavelength. The spectrum accommodates all the existing PV technologies available in the market. The results obtained were validated using Eq. (1) below. The optical scanning was conducted on areas of the coupon with the most significant accumulation since the spectrophotometer required about a 200 mm^2 space. This is to consider the worst possible case scenario and assuming that the area with less accumulation on a heavily soiled coupon was due to natural cleaning by wind, rain or gravity.

$$\boldsymbol{\tau_{solar}} = \frac{\sum_{\lambda=200nm}^{1200nm} S(\lambda)T(\lambda)\Delta\lambda}{\sum_{\lambda=200nm}^{1200nm} S(\lambda)\Delta\lambda} \quad (1)$$

Where T (λ) is the spectral transmittance, Δλ is the change in wavelength and S (λ) is the relative spectral distribution of solar radiation.

Changes in transmittance of various coupons were calculated to determine the percentage difference using Eq. (2) below.

$$\text{Relative change } (\Delta\tau_x) = \frac{(\tau_{clean} - \tau_x)}{\tau_{clean}} (\%) \quad (2)$$

where Δ is the relative change, τ_x is transmittance data of a coupon positioned at an angle relative to a horizontal surface, τ_{clean} is transmittance data of a clean coupon.

Transmittance data on Abuja's PV installation's optimum angle was interpolated using Eq. (3) below, which represents the study's local optimum angle of inclination as provided by (GSA, 2021) and could be quickly adapted for other regions when coupons are not exposed at an optimum angle of a specific area using a similar approach.

$$\tau_{\beta_{(optimum)}} = \tau_{\beta(45°)} + \frac{(\tau_{\beta(0°)} - \tau_{\beta(45°)})(\beta_{(optimum)} - \beta_{(0°)})}{(\beta_{(45°)} - \beta_{(0°)})} \quad (3)$$

where $\tau_{\beta_{(optimum)}}$ is the calculated light transmittance reduction of a coupon considering the PV optimum angle of Abuja (13°) in percentage, $\tau_{\beta_{(0)}}$is transmittance reduction data in percentage from a coupon that was horizontally positioned (90° from the vertical plane) and $\tau_{\beta_{(45)}}$ is transmittance reduction from coupons that were positioned at 45° angles. The reference is taking at 45° since its value was determined when coupons were exposed. The approach is adopted using linear interpolation to construct an unknown value of a point within two known value at discrete points. Eq. (3) is derived from a standard linear equation presented in Eq. (4) provided by Bayen and Siauw (2015). It is assumed $\mathcal{X}$-data points are in ascending order, assuming $\mathcal{X}_i < \mathcal{X}_i + 1$ and without loss of generality (Bayen and Siauw (2015).

$$\hat{\mathcal{Y}}(\mathcal{X}) = \mathcal{Y}_i + \frac{(\mathcal{Y}_{i+1} - \mathcal{Y}_i)(\mathcal{X} - \mathcal{X}_i)}{(\mathcal{X}_{i+1} - \mathcal{X}_i)} \quad (4)$$

2.3 PV Output Losses

The global solar atlas is the only reliable free online source that provides solar energy and PV potential of Abuja, Nigeria. This atlas provides easy access to solar energy resource and PV potential data around the world. The world bank funds the platform to support countries and provides information to scale up global solar energy penetration. PV output data of Abuja were provided by Global Solar Atlas (2020) considering 13°/180° as the optimum tilt angle and azimuth for PV installation. PV output specific data for a small residence with an installed capacity of 1kWp was used to illustrate PV output reduction caused by soiling influenced by various tilting coupons' positioning. The PV output was determined using the global irradiation falling on the optimum tilt plane by calculating the global horizontal irradiance, direct irradiance, terrain albedo, sun position, diffuse irradiance, and angular reflected irradiance (Global solar atlas, 2020). In addition, Global Solar Atlas considered several parameters in calculating and generating PV power output. Some of these are PV field self-shading, Nominal operating cell temperature, inverter Euro efficiency, DC soiling losses**,** DC cable losses, DC mismatch losses, AC Transformer losses, AC Cables losses and Availability. It should be noted that PV power output is for the optimum tilt angle (13°) and remains the same for all the various tilt angles in this research. Soiling losses considering the PV installation capacity, as mentioned above, was calculated for various angles using Eq. (5), Eq. (6), Eq. (7), and Eq. (8) below.

$$PV\_out_{\ (\beta_{(90)})} = PV_{(Total\ \ PV\ Output)} * (1 - \Delta\tau_v) \quad (5)$$

$$PV\_out_{\ (\beta_{(45)})} = PV_{(Total\ \ PV\ Output)} * (1 - \Delta\tau_t) \quad (6)$$

$$PV\_out_{\ (\beta_{(0)})} = PV_{(Total\ \ PV\ Output)} * (1 - \Delta\tau_h) \quad (7)$$

$$PV\_out_{\ (\beta_{(Optimum)})} = PV_{(Total\ \ PV\ Output)} * (1 - \Delta\tau_{optimum}) \quad (8)$$

Where β the angle of exposure measured from the horizontal plane, τ_t is transmittance data of a coupon positioned at 45° from the horizontal plane, τ_h is transmittance data of a coupon positioned at horizontal plane and τ_v is transmittance data of a coupon positioned at 90° from the horizontal plane.

PVSyst was employed to generate the horizon and sun path of the experiment's site (shown in Fig. 3), showing the duration of daily sun hours throughout the twelve months, and Table 1 showing the high potential of solar energy in the region. The location has high potential throughout the year, with a bit of drop during the wet season. This and the other hourly average of PV output data was used to calculate the hourly PV performance degradation caused due to dust accumulation. Eq. (5), Eq. (6), Eq. (7), and Eq. (8) were used in calculating the soiling losses of the various angles.

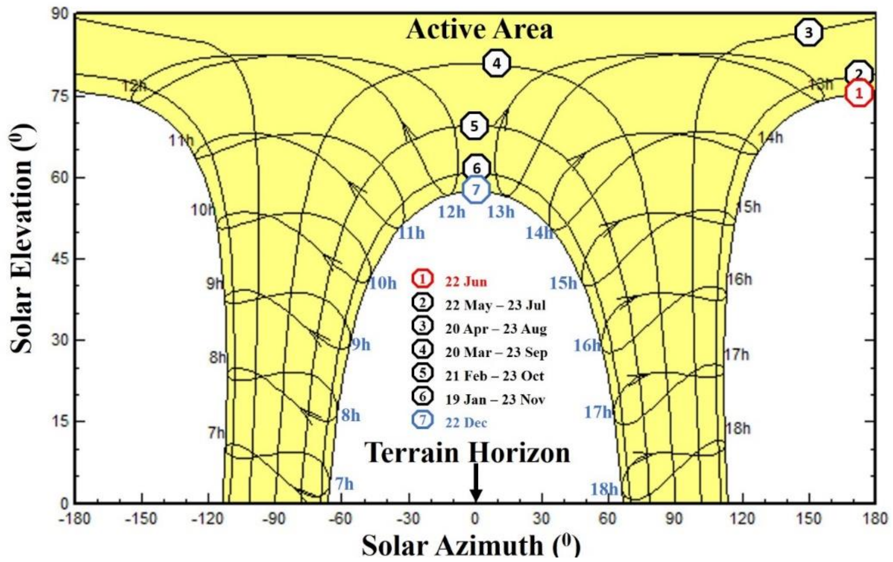

Fig. 3. Abuja's horizon and sun path (obtained from PVSyst) indicating daily sun hours for months.

2.4 Particle characterisation

2.4.1 Mass measurement

Sample weights were measured using Mettler Toledo ME204 that provides accurate and reliable weighing results, as shown in Fig. 4. Soiled coupons were initially weighed and documented. Then each coupon was washed using water and soap, cleaned with acetone, dried with a hand dryer, and reweighed again. The weight variation between a soiled and a washed coupon is the accumulated dust weight, calculated using Eq. (9). These procedures were repeated on each of the coupons to obtain the accurate weight of accumulated dust.

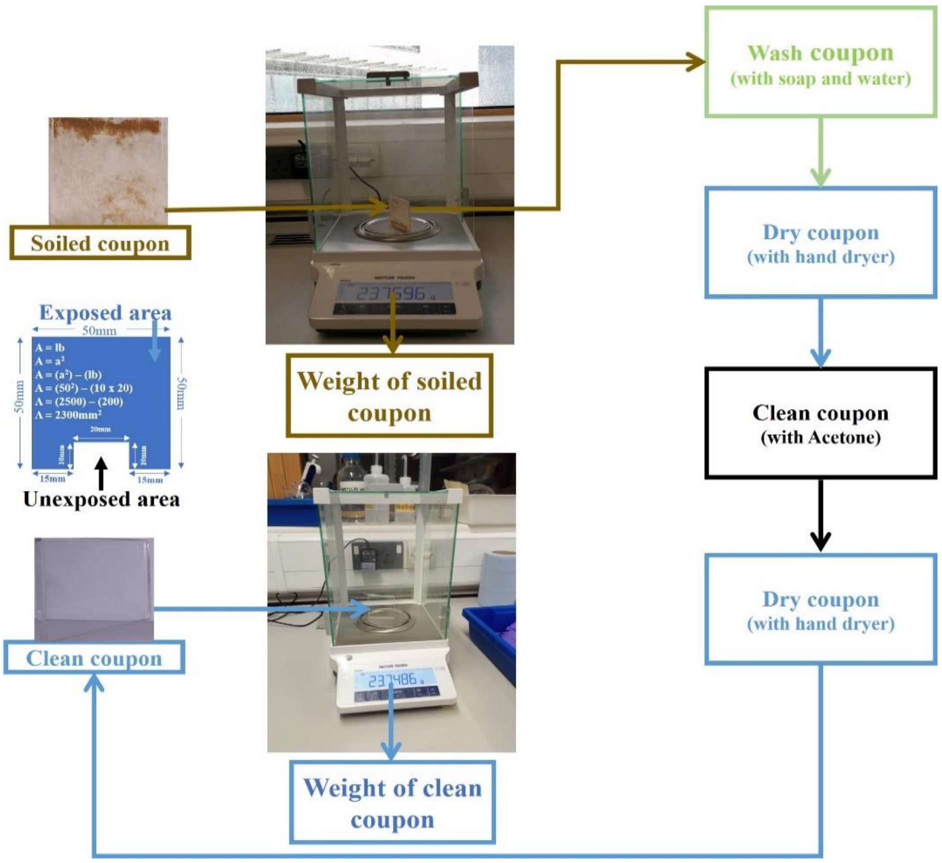

Fig. 4. Schematic for the measurement of the weight of accumulated dust on coupons.

$$\rho_d(g/m^2) = \rho A\rho dC_{(g/mm^2)} \times 10^6 - \rho AC_{(g/mm^2)} \times 10^6 \quad (9)$$

where ρ_d is the deposited dust density, $\rho A\rho dC$ is the area density of a soiled coupon, ρAC is the area density of a coupon after cleaning (clean coupon), and 10^6 is the conversion factor g/mm^2 to g/m^2 since the coupon area is 50 x 50 mm.

The exposed area of the coupon is about 2300mm^2 since about 200mm^2 was the area that goes into the holder. Surprisingly, when samples were collected back for characterisation, it was observed that a higher amount of particles accumulated around the outside the unexposed area and some particles penetrated and accumulated on the unexposed part of the coupon. Based on this, the study decided to use the entire area of the coupon rather than the exposed area alone.

2.4.2 Particles Morphology

Air quality data was obtained from Air Plume lab (2020), and horizontally exposed coupon in September 2018 was subjected to SEM (scanning electronic microscope) imaging using the SEM (S) Quanta FEG 650 to determine the size (diameter) and shapes of accumulated particle. The coupon was prepared using an Emi-Tech K950 carbon coating device to have a carbon layered that would enhance the backscattered image of the particles. This characterisation provides the reader with a better understanding of transmittance coefficient losses due to particles morphology.

3. Results and Discussion

3.1 Transmittance Losses

Transmittance losses on coupons were determined, and results were categorised and presented according to their exposure period (monthly, seasonal, and annual). Subsequent paragraphs present all other results and their analysis.

3.1.1 Monthly Transmittance Reduction due to Dust Accumulation

Average transmittance losses due to dust accumulation were determined considering different tilt angles. The monthly reduction presented in Fig. 5 and Fig. 6 shows that coupons exposed in a horizontal position cause higher transmittance reduction. The highest transmittance reduction was observed during February with a reduction of about 38% for a horizontally positioned coupon, while the most negligible transmittance reduction was observed during September, with about 1% for a vertical position coupon. The result shows that horizontally exposed coupons always accumulate more dust, followed by tilted coupons (at 45°) and then vertically positioned coupons always have the minor accumulation in all the 12 months. The observed pattern of accumulation is due to the wind effect and the gravitational force that allows the dust to settle on a flat platform, horizontal.

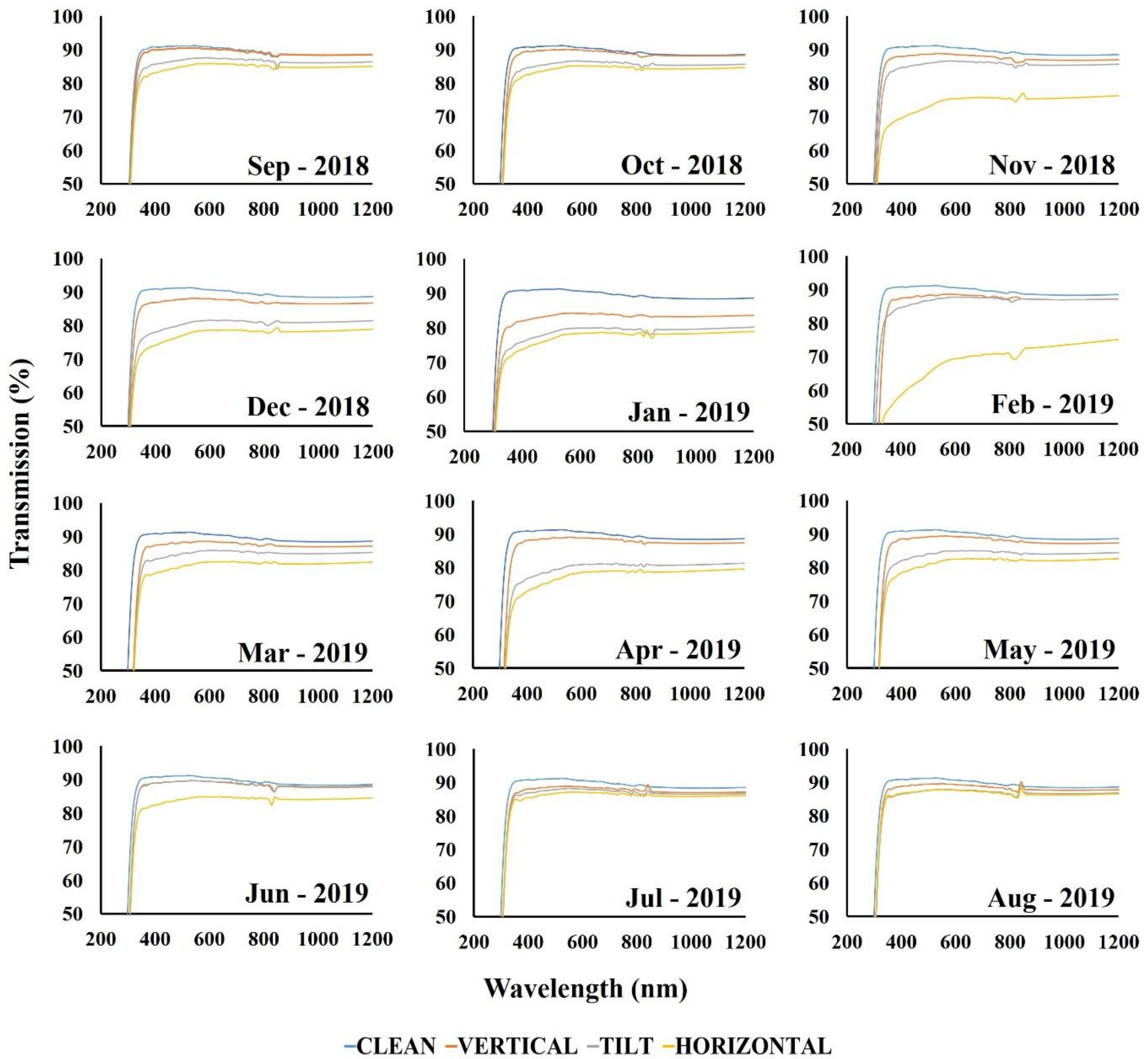

Fig. 5. Monthly optical transmittance variation for clean, vertical, 45^{O} tilt and horizontal surface of the coupons.

Using Eq. (3), the optimum tilt angle based on transmittance data was calculated for Abuja, and it was found to present alarming optical losses, as shown in Fig. 5 and Fig. 6. The highest losses were recorded from the coupon exposed on the horizontal plane followed by an optimum tilt angle which was calculated using the interpolation technique. The most significant loss based on the calculation used in determining optimum tilt angle losses was recorded for the month of February with about 17% reduction, and the lowest was recorded for the months of June and August, with both having a 5% reduction. Fig. 6 presents the calculated monthly losses and other losses obtained from exposed coupons.

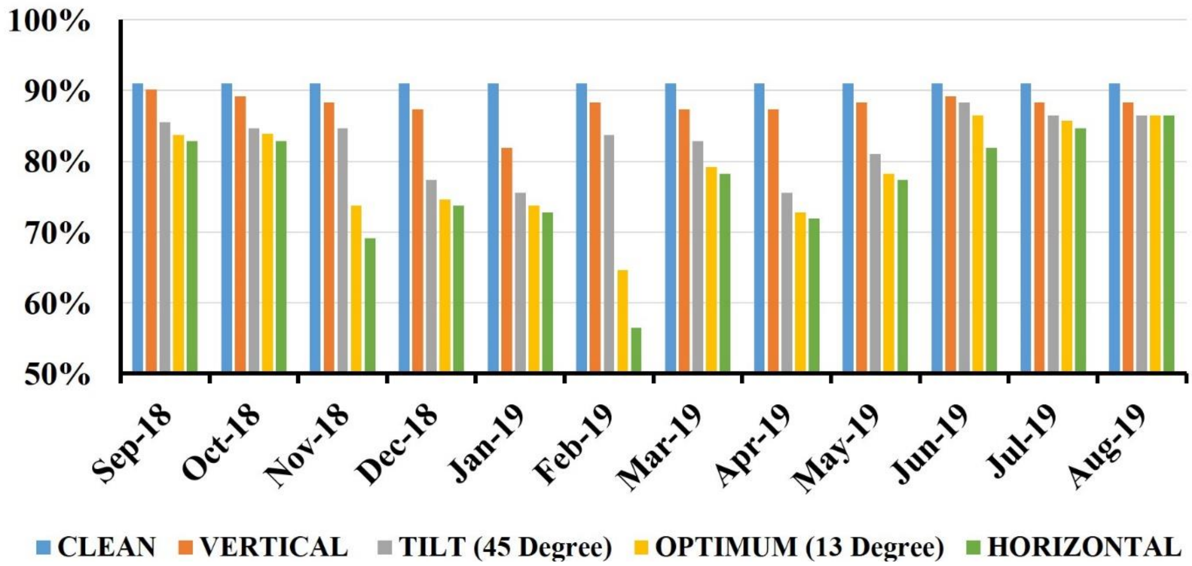

Fig. 6. Monthly variation of optical transmittance reductions for different orientation with calculated optical losses of Abuja's optimum tilt angle (13°).

3.1.2 Seasonal Transmittance Reduction due to Dust Accumulation

The seasonal transmittance reduction shows that both seasons have a severe dust accumulation, affecting the light transmittance, with the dry season having the most devastating effect. The result from Fig. 7 shows that during the dry season, a horizontal position coupon accumulates dust that causes about 88% reduction, 24% for a tilted (45°) coupon, while a vertical position coupon is about 14%. On the other hand, coupon exposed during the wet season presented a reduction of about 57% when positioned on a horizontally plane, 19% for a tilted (45°) coupon and about 15% for a vertically positioned coupon. These significant reductions of light transmittance due to dust accumulation can cause a devastating effect on the performance of PV technology. The lower amount of dust accumulation during the wet season is due to the rain that provides natural cleaning to the coupons. However, the figures are still higher and can cause a significant decrease in PV performance. The higher transmittance reductions observed during the dry season are due to a Harmattan season that blows low-level jet wind spreading dry dust across the country and lack precipitation, as highlighted in Fig. 2.

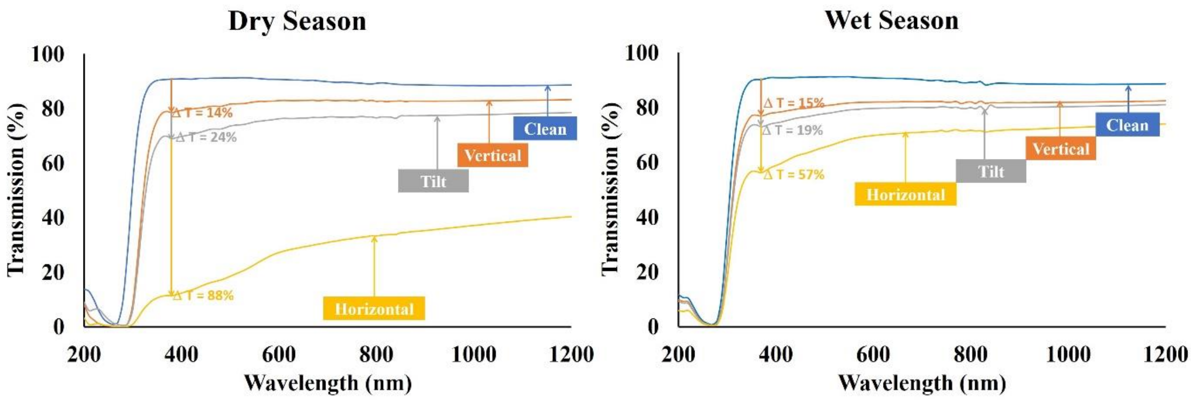

Fig. 7. Variation of optical transmittance losses for different coupons orientation that were exposed during the wet and dry season.

3.1.3 Annual Transmittance Reduction due to Dust Accumulation

The result obtained from the coupons exposed for a one-year duration shows that light transmittance reduction varies with exposure positioning. The result from Fig. 8 shows that the average transmittance of horizontally position coupon reduces by about 59%, and 42% for a tilted (45°) coupon, while the vertical position coupon is 34%. The result shows a massive accumulation of all the coupons due to the long duration of subjection to outdoor weather.

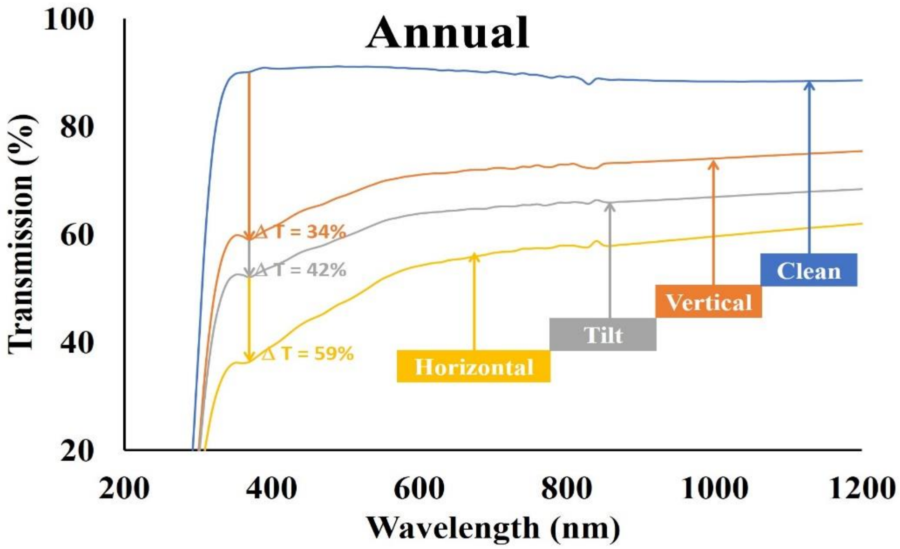

Fig. 8. Variation of optical transmittance losses for different coupons orientations that were exposed for one year in Abuja

3.2 PV Performance Reduction Considering Dust Accumulation Influenced by Tilt Angle

The PV output used in this research is a temporal aggregation, provided by Global Solar Atlas (2020) for a particular tilt angle (13°) which is the optimum tilt angle for the site of research. PV power output parameters remain the same for other angles, even though more or less power can be achieved at some times of the day for the other angle. However, this section of this research highlights and demonstrates the influence of tilt angle in dust accumulation and its effect on PV performance.

3.2.1 Hourly PV Output Losses

Hourly PV performance data were collected from Global Solar Atlas (2020) considering 1kWp installed capacity, and the monthly transmittance losses from the glass coupons were used to calculate the hourly power reduction. The result shows that significant power losses eventuated when PV installation tends to generate high output. Fig. 9 shows those months with higher outputs (November, December, January, and February) have high losses during the peak output hours compared to other months. The results also show that coupons exposed in vertical positions tend to have less power degradation than tilt (45°), optimum tilt, and horizontally positioned coupons. However, the power output used was based on the optimum tilt angle (13°); as such, the power output of other angles such as vertical, tilt (45°), and horizontal might differ with the lower value of output. The values were intentionally used since this section aims to illustrate how various angles can accumulate dust and cause severe hourly power losses.

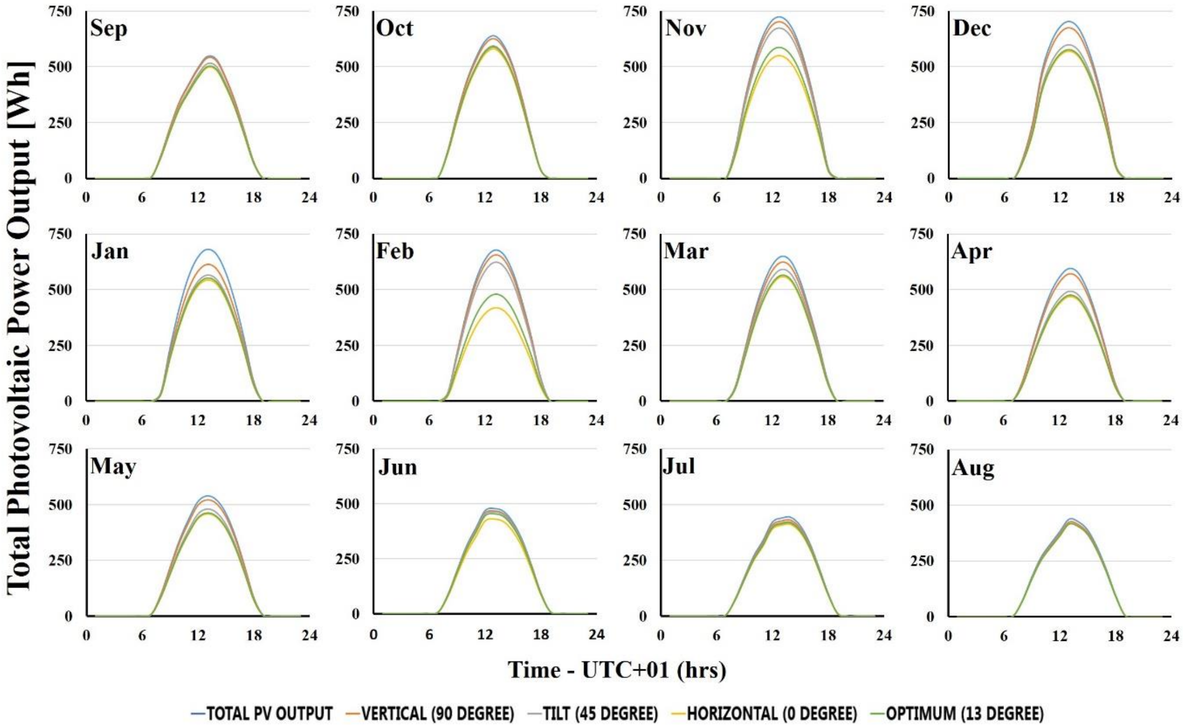

Fig. 9. Hourly photovoltaic power output variation of 1kWp rating installation and soiling losses based on optical transmittance losses recorded from coupons exposed on Abuja's various orientations.

3.2.2 Monthly PV Output Losses

The monthly PV output losses were determined using power output provided by Global Solar Atlas (2020) considering 1kWp-installed capacity and transmittance losses obtained from the exposed monthly coupons. Results show a higher degradation of PV power output on horizontally positioned coupons, and the power output improves when the angle is being tilted towards the vertical position. Results in Fig. 10 shows reductions were significantly higher during November and February, with November having 35.7 kWh/kWp losses and February having 47.1 kWh/kWp for the horizontal position coupon. Less reduction was observed on coupon exposed at an optimum tilt angle where the power degraded by about 28.3 kW for November and 35.9 kWh/kWp for February. It is observed that the degradation reduces on tilted (45°) and vertically position coupons for the two months compared to coupon on horizontal and optimum tilt with the tilted (45°) having reduction of 10.4 kWh/kWp for November and 9.9 kWh/kWp for February while the vertical position coupon degraded by 4.5 kWh/kWp for November and 3.7 kWh/kWp for February.

The lowest PV output degradations were recorded during August due to high rainfall that clean all the coupons and restore the PV's power output considering all the various tilting positions. Fig. 11 shows that reductions are similar to various tilting positions. The result shows that 5.0 kWh/kWp reduction was recorded for horizontal, optimum tilt and tilted (45°) angle coupons while the vertically positioned coupon degraded by 3.0 kWh/kWp. Fig. 2 shows that rainfall was experienced for 31 days, and according to World Weather Online (2020), an average rainfall amount of 628 mm was recorded. The high amount of rain can restore a PV surface's cleanliness but cannot be relied on since we can observe that some can still record some soiling losses.

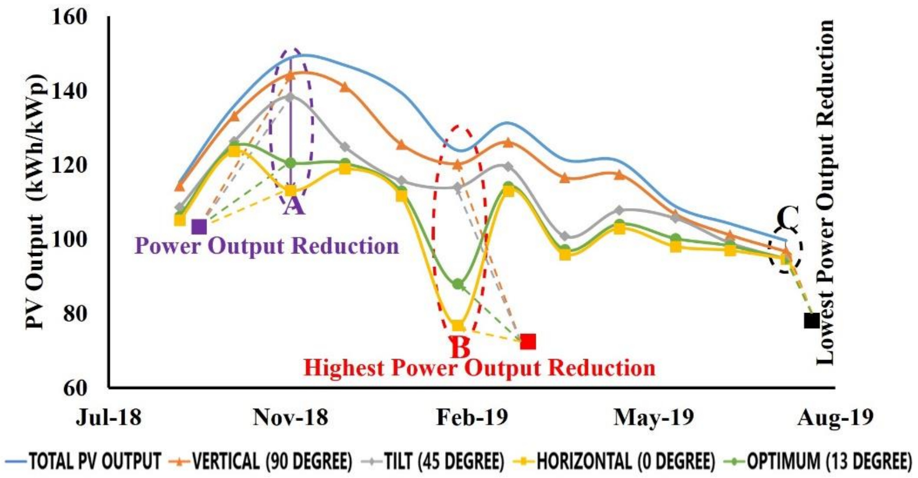

Fig. 10. Monthly photovoltaic power output variation of 1kWp rating installation and soiling losses based on monthly optical transmittance losses recorded from coupons that were exposed on various orientations in Abuja.

3.2.3 Seasonal PV Output Losses

The seasonal PV output losses were determined by taking the average power output in the months of a particular season as provided by the Global Solar Atlas (2020), considering 1kWp-installed capacity and transmittance losses obtained from the seasonal coupons that were exposed. The result from Fig. 11 shows that the summation PV output for the wet season is 937.93 kWh/kWp and the soiling losses resulted in degradation of about 141 kWh/kWp when the coupon is exposed in a vertical position, 178 kWh/kWp at a tilt angle (45°), 300 kWh/kWp at an optimum tilt angle (13°), and 347 kWh/kWp at a horizontal position. On the other hand, Fig. 11 shows that the summation of PV output for the dry season without soiling losses is about 559.07 kWh/kWp and it also presented soiling losses which caused degradation of about 78 kWh/kWp when positioned on a vertical plane, 134 kWh/kWp when on tilt (45°), 391 kWh/kWp when on optimum tilt and 492 kWh/kWp when placed in a horizontal position. The result shows that the high average degradation on both seasons was recorded when coupons were exposed to extreme condition on a horizontal plane, with the dry season having the most alarming degradation.

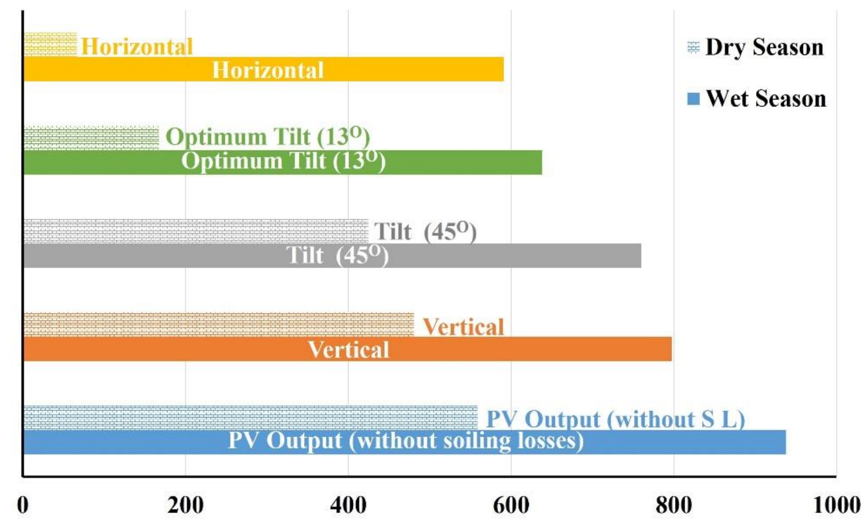

Fig. 11. Wet and dry season photovoltaic power output variation of 1kWp rating installation and various soiling losses based on optical transmittance losses recorded from coupons that were exposed on three orientations in Abuja and a calculated optical loss for the optimum tilt angle orientation.

3.2.4 Annual PV Output Losses

The annual PV output losses were determined using power output provided by Global Solar Atlas (2020) considering 1kWp-installed capacity and transmittance losses obtained from the exposed annual coupons. The result from Fig. 12 shows that an average of 1.50 MWh/kWp per year could be recorded with a PV installation having 1kWp. The result shows about 0.81 MWh/kWp per year loss is estimated due to soiling when PV is installed at an optimum tilt angle, 0.51 MWh per year for vertically position installation, 0.63 MWh/kWp per year for a tilted (45°) installation, and 0.88 MWh/kWp for a horizontal position installation. These numbers are very high, and without cleaning in just a year, soiling caused a very alarming degradation of PV performance.

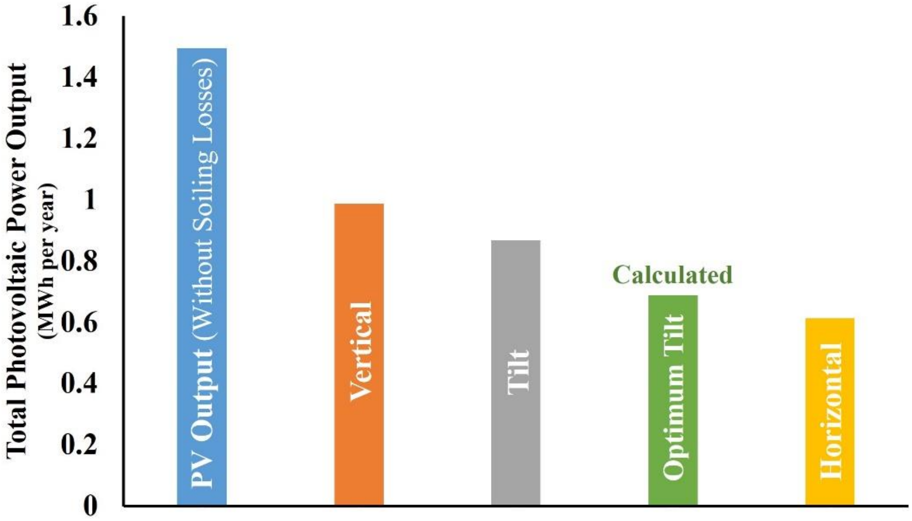

Fig. 12. The annual photovoltaic power output of 1kwp rating installation with various soiling losses was based on optical transmittance losses recorded from coupons exposed on three orientations in Abuja and a calculated optimum tilt angle optical loss.

3.3 Accumulated particles

The mass of accumulated dust as a function of tilt angle has been analysed in this report section. Results obtained clearly show how the tilt angle influences accumulation on the platform. Particles were further examined to identify morphological characters such as size, shape and diameter.

3.3.1 Monthly mass of accumulated dust

Results from monthly coupons show various weights in relation to the positioning and the period of exposure. The highest accumulations were recorded on horizontal position throughout the twelve months of the year, followed by a tilt (45°) and vertical consecutively. The horizontal coupon from February tends to accumulate more dust with about 4.16 g/$m^{2,}$ but a minor accumulation was recorded from the vertical coupon exposed during September with about 0.2g/m^2. Fig. 13 shows all the months and their corresponding dust accumulation mass and exposed position.

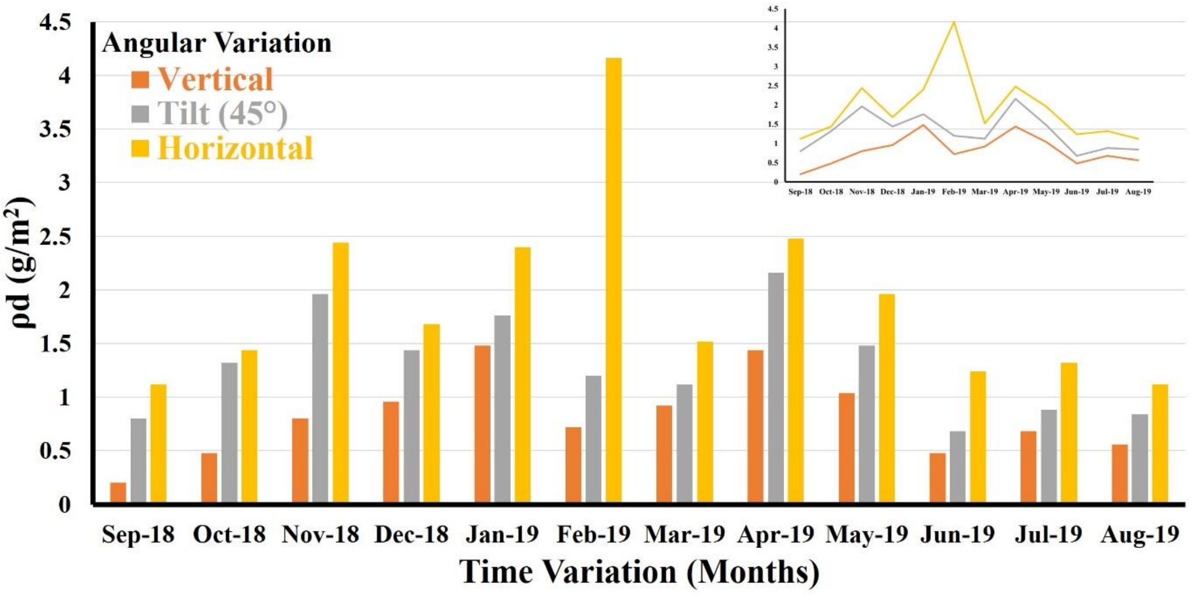

Fig. 13. Monthly variation of the mass of accumulated dust for the three orientations (vertical, 45° tilt and horizontal).

3.3.2 Seasonal mass of accumulated dust

Dust accumulation considering season (wet and dry) was evaluated, and the results obtained highlighted an alarming weight. The result from Fig.14 shows dust accumulation mass during the dry season exposed in a horizontal position, having a frightening accumulation of about 12.56 g/m^2, 2.44 g/m^2 for the tilt (45°) and 1.88 g/m^2 for vertical position. On the other hand, the result from Fig. 14 shows a less mass of accumulated dust for coupons exposed during the wet season with the coupon placed on a horizontal position, having 3.4 g/m^2, 2.2 g/m^2 for tilt (45°) and 1.76 g/m^2 for vertical position.

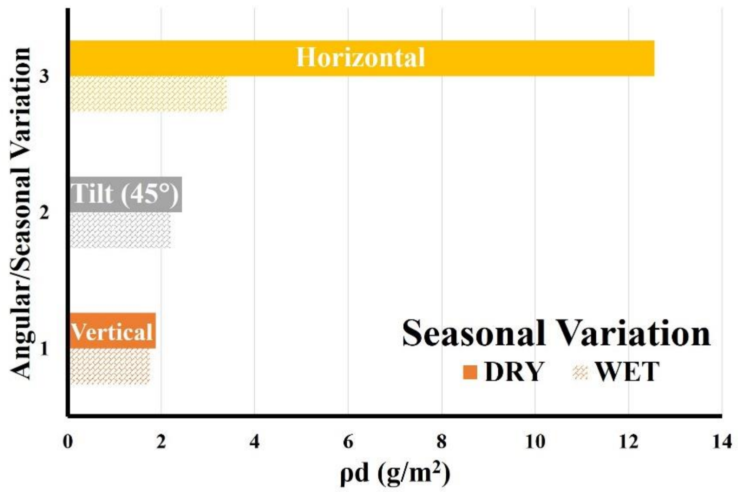

Fig. 14. Seasonal variation of the accumulated dust density showing dry season and wet season and highlighting disparity due to angular positioning in each season.

3.3.3 Annual mass of accumulated dust

Mass of accumulated dust from coupons exposed for one year is shown in Fig. 15, where the result shows that the horizontally positioned coupon is having the highest accumulation with about 8.52 g/m^2, followed by the coupon exposed on tilt (45°) position with about 3.84 g/m^2 and the least is the vertical position with about 3.24 g/m^2.

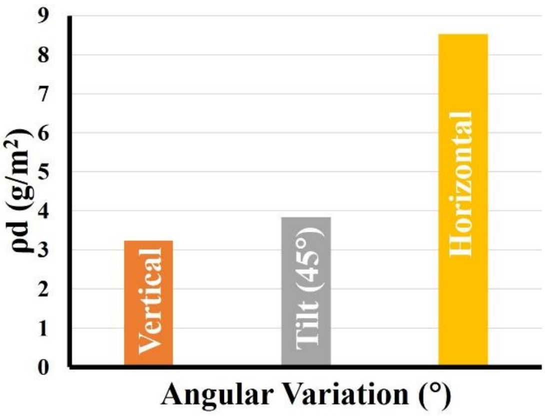

Fig. 15. Variation of the mass of accumulated dust for one year in relation o angular positioning.

The high mass of accumulated dust on coupons exposed in the horizontal position presented above is related to gravitational forces and weather condition. In addition, the transmittance coefficient loss in correlation with the weight of accumulated dust on the coupon was presented in Fig. 16. Moreover, illustrating how the reduction in transmittance continues to increase as the weight of accumulated dust increases.

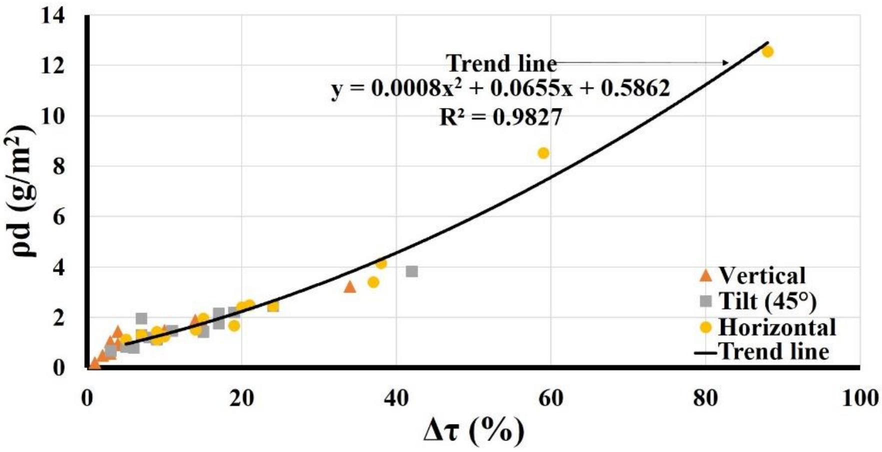

Fig. 16. Transmittance coefficient losses verse dust density with a polynomial trend line illustrating their correlation.

Dust accumulation as a function of the tilt angle is presented in Fig. 17. Furthermore, illustrating how the influence of tilt angle plays a significant role in dust accumulation. The result shows that when coupons are positioned on a horizontal plane, they tend to have a higher mass than tilt (45°) and vertical position, with vertical being the one with less weight. Similarly, this pattern of accumulation occurs on all the coupons for various exposure periods.

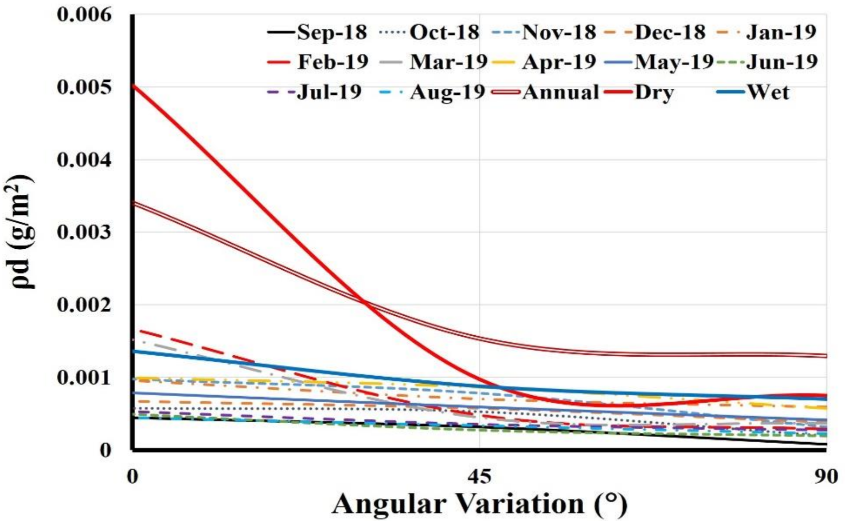

Fig. 17. Variation of dust density as a function of angular positioning.

The result obtained from the mass of accumulated dust validate our transmittance and power output reduction result presented above and corroborated with the result presented in literature from other similar studies mentioned above.

3.3.4 Particles Morphology Characterisation

The air quality index shows a higher concentration of PM_{10} and $PM_{2.5}$ in the atmosphere. The findings from coupon subjected to SEM imaging show large sizes of particles, which is further illustrated in Fig. 18, where the variation of particles sizes and shapes and several PM_{10} and $PM_{2.5}$ were observed. This coupon is among the ones with a minor accumulation; therefore, it is assumed that others with more soiling could show higher particles settlement.

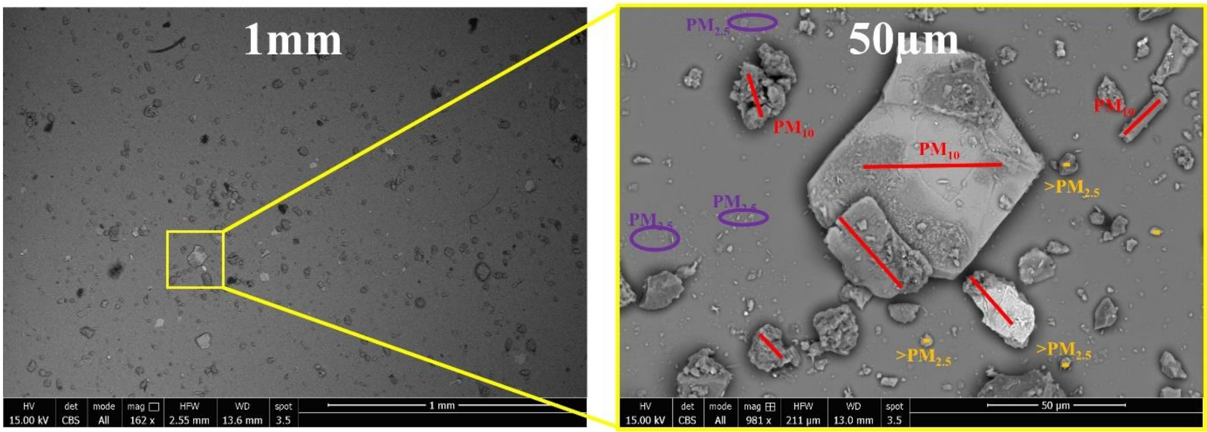

Fig. 18. SEM imaging illustration particle sizes and their shapes.

According to Air Plume Labs (2020), the air quality index for February is the highest, indicating 194 AQI categorised as unhealthy and harmful to some sensitive groups. Main pollutant are categorised as $PM_{2.5}$ = 164AQI, PM_{10} = 194AQI, NO_2 = 14AQI, and O_3 = 32AQI while $PM_{2.5}$ = 96µg/m^3, PM_{10} = 231µg/m^3, NO_2 = 28µg/m^3 and O_3 =70µg/m^3. These figures clearly show the reason why high accumulation was recorded during the month.

4. Discussion

Transmittance reduction was recorded on all the exposed coupons with a higher reduction on the horizontally positioned coupons, gradually increasing with tilt angles (45°) towards the vertically positioned coupons. Considering the weather data provided in 2, it is clear that there is less or zero precipitation during the dry season months and the wind velocity is low. It is observed that the highest accumulation was recorded on the horizontal position coupon during February. Another reason is the light rain that occurred and promotes capillary bridges between dust particles to cause more adhesion on the coupons, thereby resisting the wind effect. The positioning also contributes by reducing sliding and rolling of particles to retain more particles on the surface.

A variation was observed on some wavelengths in Fig 5, with a more noticeable decrease around UV wavelength attributed to the different types of accumulated dust particles, their morphology (precisely size), chemical composition, and deposition pattern. The majority of the existing PV technology's spectral response is from hundreds of nanometre as such a particle with a diameter of around less than a micron could cause light attenuation. As earlier provided, the AQI parameters recorded in the region showing a higher concentration of PM_{10} and $PM_{2.5}$ and related to dust particles characterisation provided by Chanchangi et al. (2020a). It was assumed that the variation is due to broader particle diameter and the decrease in wavelength since UV wavelength could be easily affected by a tiny particle. It is also related to the natural deposition that is usually non-uniform. Gholami et al. (2017) stated that whether using PV devices or solar collectors, solar radiation needs to pass through the covering material, mainly glass or plastic, before exciting the technologies to generate heat or electricity. Therefore, the transmittance coefficient of the PV covering material is vital for device performance and anything that affects it could cause performance degradation.

Fig. 7 shows a broader variation during the dry season, especially on horizontally position coupon compared to other orientations in the same season and also compared to the wet season. A similar variation was observed in Fig. 6; this time, the seasonal variation effect was sub-divided into months. The disparity is related to weather and gravitational force during the dry season, where dominant inward wind flow has more effect on accumulated particles on the vertical and tilt orientation, causing re-suspension of a significant amount. When the wind velocity drops and the weather tends to be calm, the relative humidity sometimes builds up to develop water droplets at specific points or dew build-up, and these could quickly settle on a horizontal surface compared to other orientations. Furthermore, during the daytime, when the relative humidity is dropping and the temperature rises, dry, dusty weather comes and mix with the water droplets, cementation would occur to retain a significant amount of particles. Fig. 2 shows a slight increase in precipitation and humidity at the beginning and towards the end of the dry season, which plays a vital role in causing cementation. When cementation and capillary ageing occurs on a surface, it is challenging for the wind to cause rolling, lifting and sliding since the incoming wind would have less access to an acting force (capillary force) and nearly no access to another acting force (Van de Waal force). This corroborates with Hee et al. (2012), where they demonstrated how an inward wind reduces accumulation on a facing coupon and more reduction in rainfall. Also, higher mass was recorded on coupons exposed during the dry season wet season, as shown in Fig. 14.

Fig. 9 shows wide gaps between potential PV output and output losses during peak hours in months with higher PV outputs (November, December, January, and February) and higher transmittance losses. The illustrated wider gaps or losses are directly related to the increase in solar irradiance, which does not penetrate the accumulated particles on the coupon. The months comes with high solar irradiance, less cloud and zero - less precipitation, but the soiling rate is higher, as shown in Fig 2. Therefore, accumulated dust would tend to have a higher impact on high solar irradiance since more obvious losses can easily be observed. When using a constant soiling rate, it would be observed that the transmittance losses tend to increase as the irradiance level increase.

The wind effect tends to have a more negligible effect on the accumulated particles on the horizontal surface than a tilted one (45°), resulting in more accumulation. Vertically positioned coupons were observed to have less accumulation on all the setup. It is due to less exposure to the angle of attack of the wind flow. The airflow sometimes tends to contact the coupon at a right angle, causing a high increase in dust particle detachment. On a vertically positioned, the rain has no platform to settle as such washes of particles on the coupons. Figgis et al. (2019) stated that a high increase in dust particle detachment could be observed by fast near-wall flow (air or water). Tilted (45°) positioned coupons were observed to have moderate accumulation on all the setup due to the obtuse angle created and facing the wind that promotes high deposition and detachment of particles. It was observed that horizontally positioned coupons accumulated more dust compared to others. As earlier stated, it is due to gravitational effects. These coupons also retain more water on its surface after rain and, when they become dry, they tend to form strong cemented material on the surface. Cano et al. (2014) have confirmed this observation by stating that platform tilted at angles less than 15° retains a higher amount of water on their surface after rainfall. In addition, coupons are not exposed to maximum airflow; therefore, the wind tends to have a lesser detachment effect on particles, which can cause detachment of particles. Figgis et al. (2019) stated that airflow tends to have a more negligible effect on the coupon on the steeper tilting angle, reducing particles' detachment. It was observed that average monthly wind velocity at the experiment site tends to be greater than 4 m/s and Gholami et al. (2017) stated that wind velocity above 4 m/s could play a critical role in determining the accumulation rate on surfaces. Ilse et al. (2018) show detachment could occur due to wind velocity of 10m/s through rolling, sliding, and lift-off, but the angular position of the surface was neglected, which could play a vital role. It is assumed that a significant amount of dust has been re-suspended due to direct contact with an inflow of high wind speed and particles/adhesion forces acting on them.

The gravitational force allows more dust to gravitate and settle on a horizontal and tilt platform (45°) compared to a vertical position platform. The particles illustrated in Fig. 18 and the air quality data presented above show large particles size, and the gravitational force tends to significantly influence particles with a wider diameter and higher mass. However, it is negligible when the particle's diameter is small. Ilse et al. (2018) provided an illustration and simulation of how particles greater than 2.5 µm could be influenced to settle on a horizontal surface due to gravity.

According to Air Plume Labs (2020), the region's air quality index shows a significant concentration of PM_{10} in the atmosphere and appears to be the greatest. Similarly, many of the accumulated particles appear larger and have angular shapes with almost flattened top. Some of the shapes are angular, quadrangular, aggregated angular and rounded layered structure. Based on the PM and the shapes of the particles observed from the SEM image from Fig. 18, the accumulated dust is assumed to have a high concentration of coarse sand and loamy soil from construction sites, agriculture and windblown dust. These kinds of particles tend to settle quickly on a flat surface rather than a tilted or vertical platform due to gravity acceleration influenced by their weight.

It was observed that coupons appear to have a non-uniformity pattern of deposition, and the disparity rate varies with angular positioning. It was observed that some homogenous pattern of accumulation tends to occur on vertically positioned coupons, but it was not 100% similar. These coupons have small accumulations, and the difference was hardly detected easily with bear eyes. The tilted (45°) and horizontally positioned coupons have areas on their surfaces with an aggregated pattern of accumulation and were observed on the coupons with higher accumulation (November, February, dry season and annual coupons). The horizontally positioned coupons for the annual and dry season show a multi-layered and sectional aggregated accumulation pattern.

The results obtained from this study was compared to other similar studies. Table 2 compares transmittance results with other studies (Hegazy, 2001; Elminir et al., 2006; Abdolzadeh and Nikkah, 2019) that have similar reductions. It also shows that higher transmittance reduction was found on the horizontal position coupon, with a gradual increase in light transmittance as the tilt angle increases towards a vertical position, except for research presented by Gholami et al. (2017). The study shows that the highest transmittance reduction was recorded on the tilt angle, followed by horizontal and then vertical when coupons faced the opposite side of the dominant incoming wind direction.

Table 2: Comparison of transmittance results with published works

Research	Location	Period of Exposure	Vertical	Tilt	Horizontal
Hegazy (2000)	Minia, Egypt	**30 days**	4%	40^0 = 12% 50^0 = 15%	27%
Elminir et al. (2006)	Cairo, Egypt	**7 Months** (Dec –Jun)	13%	45%	52.54%
Qasem et al. (2011)	Safat, Kuwait	**30 days**	0.21	1.00	1.98
Said and Walwil (2014)	Dhahran, Saudi Arabia	**45 days**	2%	7.5%	10.5%
Gholami et al. (2017)	Isfahan, Iran	**70 days** (May – Aug)	West = 24%	West = 24.7 %	West = 24.6%
Sisodia and Mathur (2019)	Jodhpur Rajasthan, India	**Annual**	24%	13%	31%
Abdolzadeh and Nikkhah (2019)	Kerman, Iran	**Monthly**	June = 8%	June = 11.5%	September = 15%
		Seasonal	Winter = 3.4% Spring = 4% Summer = 8% Autumn = 5.9%	Winter = 4.5% Spring = 6.5% Summer =11.5% Autumn = 10%	Winter = 5.2% Spring = 7% Summer =13.5% Autumn = 15%
This work	Abuja, Nigeria	**Monthly**	January = 10%	April = 15.5%	February = 38%
		Seasonal	Dry = 14% Wet = 15%	Dry = 24% Wet = 19%	Dry = 88% Wet = 57%
		Annual	32%	42%	59%

PV tilting position influences its power output reduction due to dust accumulation. The results above demonstrate reductions in PV power output in a location with high solar energy potential and atmospheric dust activity. The result also demonstrated how angular variation causes a disparity in PV output with the horizontal position, having the highest degradation rate followed by an optimum tilt angle, tilt angle (45°), and vertical angle the lowest. Other research (Elminir et al. 2006; Hachicha et al., 2019; Sisodia and Mathur, 2019; Abdolzadeh and Nikkhah, 2019) highlighted in Table 3 confirmed that the tilt angle influence dust accumulation, which causes PV performance degradation.

Table 3: Comparison of PV output performance reduction results with published works

Research	Location	Period of Exposure	Vertical	Tilt	Horizontal
Elminir et al. (2006)	Cairo, Egypt	**7 Months** (Dec –Jun)	5 mW	20.5mW	35 mW
Hachicha et al. (2019)	Sharjah, United Arab Emirates	**6 Months**	N/A	10.95%	37.63%
Sisodia and Mathur (2019)	Jodhpur Rajasthan, India	**Annual**	16.5%	10.5%	23.8%
Abdolzadeh and Nikkhah (2019)	Kerman, Iran	**Monthly**	November = 6.7%	June = 10.9%	September = 12.6%
		Seasonal	Winter = 2.4% Spring = 3.2% Summer = 6.8% Autumn = 6.6%	Winter = 3.2% Spring = 4.6% Summer =9.6% Autumn = 9%	Winter = 3.8% Spring = 6% Summer =12.6% Autumn = 12.6%
This work	Abuja, Nigeria	**Monthly**	January = 10%	April = 15.5%	February = 38%
		Seasonal	Dry = 14% Wet = 15%	Dry = 24% Wet = 19%	Dry = 88% Wet = 57%
		Annual	32%	42%	59%

The weight of accumulated dust based on angular dependencies shows an increment with a vertical angle towards the horizontal position. It is recorded that the weight of accumulated dust decreases as the tilt increase towards the vertical position. As presented in the result section, the increment of accumulated dust's weight is directly proportional to light transmittance reduction; as the weight increases, the light penetration reduces. The highest accumulated dust weight was recorded on a horizontally positioned coupon, while the lowest was recorded on a vertically positioned coupon.

Results obtained was validated considering other publication (Hegazy, 2000; Elminir et al., 2006; Said and Walwil, 2014; Gholami et al., 2017; Abdolzadeh and Nikkah 2019) highlighted in Table 4.

Table 4: Comparison of the mass of accumulated dust obtained with other published works.

Research	Location	Period of Exposure	Vertical	Tilt	Horizontal
Hegazy (2000)	Minia, Egypt	**30 days**	0.5 g/m^2	2.45 g/m^2	7 g/m^2
Elminir et al. (2006)	Cairo, Egypt	**7 Months** (Dec –Jun)	5 g/m^2	14 g/m2	15.84 g/m2
Said and Walwil (2014)	Dhahran, Saudi Arabia	**45 days**	0.8 g/m^2	4.5 g/m^2	6.5 g/m^2
Gholami et al. (2017)	Isfahan, Iran	**70 days** (May – Aug)	5 g/m^2	5.5 g/m^2	5.2 - 6 g/m^2
Abdolzadeh and Nikkhah (2019)	Kerman, Iran	**Monthly**	2.2 g/m^2 – June	2.7 g/m^2 - September	4 g/m^2 - September
		Seasonal	2.2 g/m^2 – Summer	2.7 g/m^2 - Autumn	4 g/m^2 - Autumn
This work	Abuja, Nigeria	**Monthly**	Jan – 1.4 g/m^2	Apr – 2.16g/m^2	Feb - 4.16 g/m^2
		Seasonal	Dry – 1.88 g/m^2 Wet – 1.76 g/m^2	Dry – 2.44 g/m^2 Wet – 2.2 g/m^2	Dry – 12.56 g/m^2 Wet – 3.4 g/m^2
		Annual	3.24 g/m^2	3.84 g/m^2	8.52 g/m^2

Evidently, the results obtained show a substantial reduction of transmittance due to dust accumulation when coupons were exposed to Abuja's outdoor condition. The dust accumulation rate on a surface is related to coupon positioning (Tilt angle) with the highest dust density at horizontal and gradually decreases as the angle is tilted towards the vertical position. However, although findings show that the angular orientation has a significant influence on dust accumulation rate, there are other parameters such as weather condition (wind speed and direction, humidity and temperature), particles, PV covering materials (such as acrylic plastic and low iron glass), location, and period of exposure. These parameters could significantly influence deposition and accumulation, and some might be more sensitive than angular orientation. This is in line with some studies such as Gholami et al. (2020), Gupta et al. (2019) and Chanchangi et al. (2020). PV covering materials also influence accumulation, where plastic is reported to have a greater accumulation rate than low iron glass (Chanchangi et al. 2020a). Whichever tilt angle the PV devices are being installed on, the technology cannot be left unattended. Considering the result obtained and other published research works on Table 2, Table 3, and Table 4, it is confirmed that tilt angle is an influencing factor for dust accumulation in Abuja and every location around the world, which requires continuous maintenance even during the wet season when certain level cleaning is provided naturally by precipitation. Since results highlight periods of high soiling in Abuja, the information could be used to predict soiling activities in the region and provide guidance for maintenance where the optimal timing for mitigating dust on PV can be performed. Chanchangi et al. (2020a) and Gholami et al. (2017a) provide some mitigating soiling methods, which could be used to prevent or restore the PV performance capacity.

5. Conclusion

To improve the penetration of solar PV technology and reduce greenhouse gas emissions in Nigeria, the effect of dust accumulation on PV performance has been investigated, considering tilt angle as an influencing factor. The influence of different tilt angle on dust formation in Abuja (capital of Nigeria; 9.06° N, 7.46° E) has been determined with accumulations causing significant reductions of light transmittance from exposed coupons. The monthly results highlighted that horizontal position could cause dust accumulation leading to transmittance reduction from 5% to 38% for one month, 45° tilt position is from 3% to 17%, while the vertical position from 1% to 10%. The seasonal results indicate an 88% transmittance reduction for a coupon exposed on a horizontal plane during the dry season and 37% during the wet season. For the 45° tilt position, 4% was recorded during the dry season and 19% for the wet season, while the vertical position is 14% for the dry season and 15% for the wet season. The annual results indicate a similar dust accumulation trend showing transmittance reduction of about 59%, 42%, and 34% for horizontal, tilt (45°) and vertical positions. These reductions of light transmittance resulted in a corresponding degradation of power performance output. The results illustrated how the PV tilt angle influences dust accumulation density, with higher mass recorded on coupon exposed to extreme condition on horizontal position compared to tilt (45°) and vertical. In conclusion, the soiling rate is attributed to PV surface positioning (tilt angle) with the horizontal position accumulating more, and the density slowly decreases as the angle becomes inclined towards the vertical direction. However, other parameters such as weather condition, particles characteristics, PV covering materials, location, and exposure period could significantly influence the accumulation, and some might be more sensitive than angular orientation.

Dust deposition and accumulation are two different parameters with dust accumulation to be the essential factor to be considered since it has been proven based on the above result that tilt angle can have a more significant influence on accruing dust on surfaces, which can lead to the reduction of transmittance and PV power output degradation. The finding shows that emerging PV technologies such as solar blocks, blinds, interior decorations, vehicles, windows, and roofs with angular positioning restriction could have their advantage of not accumulating higher particles that could require more maintenance cost when positioned at angles other than horizontal plane. The technologies could be integrated into traffic facilities, parking bays, vehicle parts, buildings and industries to reduce the load from grids. This study recommends that governments should provide funding to determine the soiling rate at various angular positioning in its region using this cost-effective and straightforward approach provided since the soiling rate is location-specific due to this factor other additional ones identified in this study and other similar reports. It also recommends that government provide incentives such as tax holidays and low tariffs on PV to promote its penetration for swift utilisation of various solar technology mentioned above to reduce greenhouse gas emissions. It is recommended that the solar panel positioning in a horizontal plane be avoided where possible as long as PV performance is not compromised. The result obtained provided soiling periods. The information could be used to forecast soiling events in the region, which can be used for planning maintenance, where optimal scheduling for prevention and restoration of PV performance can accelerate its penetration and minimise emission. This research strongly emphasised the need to investigate various mitigation techniques in the region to identify the most appropriate one for optimum prevention and restoration of the technology's performance during its operational life cycle and similarly in other regions with high solar energy potential and high amount of dust in the atmosphere.

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