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Soiling mapping through optical losses for Nigeria

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Abstract

Soiling consists of the accumulation of dust on the solar panel's surface and has a deleterious effect on solar photovoltaic devices' performance, which varies with location. However, soiling losses and rates are significantly under-reported or underestimated since regional differences and seasonal variations are overlooked. Accurate prediction of PV soiling losses for a particular location can save revenue losses associated with a solar PV system. This research investigated the effect of soiling on PV performance through optical losses by employing a low-cost soiling station. Low iron glass coupons (5 mm x 5 mm) were exposed on three angles (vertical, tilt-45°, and horizontal) in seven sites across Nigeria to collect annual, seasonal and monthly soiling data. Each coupon was then subjected to optical characterisation using a spectrometer and imaging analysis using the SEM/EDX. The finding shows significant optical losses across the country, with all the highest rates recorded on coupons exposed on the horizontal plane, where the maximum loss of 88% was recorded on the Abuja, North Central (ABV) coupon. SEM/EDX finding illustrated minerals with the potential to affect light transmittance, and the pollutant data confirmed the particles. The optical results were further employed to map the soiling distribution across the country. A wide deviation was observed from the data on the Global Solar Atlas, as it disproportionately underestimated the soiling losses across the world.

Keywords: Optical losses; PV soiling; Mapping; Dust Particles; Nigeria

Nomenclature

$S(\lambda)$	Relative spectral distribution of solar radiation
$T(\lambda)$	Spectral transmittance
$\Delta\lambda$	Change in wavelength
P_{out}	Power output
τ_{clean}	Transmittance data of clean coupon
τ_x	Transmittance data of an exposed coupon on an unknown angle
$\Delta\tau_x$	Change of transmittance data of an exposed coupon on an unknown angle
$\Delta\tau_{(Optimum)}$	Calculated change of transmittance of a coupon at an optimum angle
$\beta_{(x)}$	The optimum tilt angle of a particular station
$\beta_{(0)}$	Horizontal plane (angle 0°)
$\beta_{(45)}$	The tilt angle of 45°
$\Delta\tau_{(0)}$	Soiling losses recorded on a coupon positioned on a horizontal plane
$\Delta\tau_{(45)}$	Soiling losses recorded on a coupon positioned at angle 45°
Z_K^*	The smooth estimate produced by Kriging interpolation
λ_i	Weight for Z_i
Z_i	Variable
Z_V	Actual value
$\bar{C}(V, V)$	Covariance between the variables of the samples
μ	Lagrange parameter
$\bar{C}(v_i, V)$	Covariance between the estimations and the variables of the samples
CO	Carbon Monoxide
O ₃	Ozone

NO ₂	Nitrogen oxide	28
SO ₂	Sulphuric oxide	29
PM ₁₀	Particulate Matter 10 micrometres and smaller	30
PM _{2.5}	Particulate Matter 2.5 micrometres and smaller	31
		32
		33

34

Units		35
µg/m ³	Microgram/meter cube	36
kWp	kiloWatt peak	37
MW	MegaWatt	38
mm	millimetre	39
		40
nm	nanometer	41
		42
		43

44

Abbreviation	
3D	3 Dimension
ABS	Acrylonitrile Butadiene Styrene
ABV	Abuja
AQI	Air Quality Index
BSE	Back Scattered Electron
EDX	Energy Dispersive X-ray
ENU	Enugu
ESMAP	Energy Sector Management Assistance Program
GIS	Geographical Information System
GSA	Global Solar Atlas
GW	Giga Watt
IEA	International Energy Agency
KAD	Kaduna
LOS	Lagos
MENA	The Middle East and North Africa
MIU	Maiduguri
NIR	Near Infra-Red
PHC	Port Harcourt
PV	Photovoltaic
RE	Renewable Energy
SE	Secondary Electron
SEM	Scanning Electron Microscope
SMS	Small-Medium Scale
SOK	Sokoto
UV	Ultra-Violet
VIS	Visual
WHO	World Health Organization

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46 1 Introduction

47 Solar photovoltaic (PV) is rapidly penetrating the global energy market, having an annual additional
 48 capacity of about 115 GW and a total capacity of 627 GW in 2019 [1]. However, the technology faces
 49 environmental challenges such as soiling, which has a detrimental effect on its performance, as reported
 50 in a number of publications [2-5]. Soiling is a factor that can degrade the performance of PV by reducing
 51 the amount of incident transmitted light upon solar cells. The losses due to soiling vary with location,
 52 human activities in the region, PV systems' design, angular position, mounting orientation, surface
 53 covering material, and climate [6, 7]. The reported soiling loss rates range from as low as 0.5% reduction
 54 of PV output in a day [8], 63% in a month [9], to about 50% reduction of PV yield in 6 months[10]

without cleaning. A clean low iron glass has 91% transparency [11], reducing the amount of irradiance reaching the solar cells and preventing them from generating optimum yield. Since the most commonly used and one of the best PV covering materials available in the market already possesses some transmittance limitations, there is a need to prevent or reduce any further optical losses to ensure that maximum irradiance reaches the solar cell to harvest higher yield. As stated earlier, the soiling loss rates cannot be constant for different regions since they vary with the location, depending on the human activities and the climate. Some research works reporting loss variation in various regions are provided in the supplementary material.

Employing a constant value as a soiling loss cannot be accepted as it would illustrate an unrealistic PV potential of a region. Standards assume fixed soiling loss values, such as $\pm 5\%$ in the AS4509.2 (3.4.3.6) [12], 2% and 3% in SAND2014-19199 [13], and 3% in Enphase Energy [14], which might be grossly inappropriate for some regions. Tanesab et al. [15] recommended reviewing soiling rates and considering regions with high solar energy potential and extreme weather conditions. In addition, the Global Solar Atlas (GSA) [16] used constant soiling loss values for categories of installation, such as; 3.5% for 1kWp, 4.5% for small residential, 4% for medium commercial, 3.5% for large scale, and 6% of floating large scale. However, GSA [16] clearly stated that the PV yield they provide is an estimation value as some important factors (such as soiling) are not adequately calculated. The Global solar atlas (GSA) is a platform that provides solar energy resources across the globe; which SolarGIS and finance were developed by the Energy Sector Management Assistance Program (ESMAP) through the World Bank fund. The GSA provided solar information like no other; it is the best platform available so far that provided introductory-level data that could help researchers, policymakers, and PV companies decide. These values grossly underestimate the magnitude of PV yield degradation that soiling losses could cause in some regions across the world, especially the Middle East and North Africa (MENA), Saharan, sub-Saharan Africa, and regions with high dust atmospheric dust.

Li et al. [17] investigated the soiling on fixed, one-axis tracking (OAT) and two-axis tracking (TAT) modules employing modelling techniques to develop a map using 12 years of particulate matter, global solar irradiance, and precipitation data. The study reported a more than 50% PV yield reduction for heavily polluted areas such as the Middle East, Africa, and China. However, this study ignored a crucial factor (such as wind) that can significantly influence deposition when its velocity is low and acts as natural cleaning when its speed is high, thereby overestimating deposition rate/accumulation and underestimating natural removal rate [18-21]. The study does not provide details on the soiling losses in Western, Central, and Eastern Africa, subject to substantial dust generation levels due to their geographical terrain, human activities and proximity to the largest global dust generation region, the Sahara desert.

Mithu et al. [22] developed a soiling map to illustrate the global PV soiling and predict revenue loss considering regional optimal cleaning frequency using reported experimental data of 132 sites from literature. Their finding shows that Asia has the highest soiling rate of 1%–2%/day, followed by the Middle East with 0.7%–1.5%/day, mid-Africa (between 0 and 15°N latitudes) with 0.5%–1%/day and the rest of the world mostly below 0.5%/day. They predicted a global revenue loss for the optimal cleaning cycle to be around 1%–5.5%. Modelling global data using 132 sites from reported experimental results that might have become obsolete to develop a global map could vastly underestimate and underreport the value of some regions, such as West Africa and Central Africa, where only two reported values were used for the entire map.

Micheli et al. [23] developed a regional soiling map by employing five spatial-interpolation approaches extracted from PV performance and soiling station data to estimate nearby sites in the United States of America (USA). Their findings show that an average soiling ratio could be estimated with a root-mean-square error (RMSE) of 1.4% and coefficients of determination of about 74%. Their analysis shows that the error could be reduced to 1.1% when soiling sensors are deployed to determine the soiling rate compared to estimation, with about 78% determination coefficient variation between determined and estimation values. Their findings show that deploying sensors will reduce errors, especially when the distance between sites is reduced to below 50 km. Although the study used soiling station and PV performance data from 83 sites across the United States and laid a foundation for this kind of study, the

study ignored weather parameters related to soiling and other influences such as temperature and cabling losses, shading losses and other parameters.

Cordero et al. [24] reported the effect of soiling on PV performance, where findings were illustrated in a map. The study was conducted in five sites around the Atacama desert, which transect approximately 1300 km from latitude 18° S to latitude 30° S. Four PV modules were deployed where two were cleaned, and the others were left to accumulate dust. The finding shows a 39% (in Arica, a city around the Atacama desert) annual PV yield reduction in the northern region and 3% or less in the southern part (Copiapo, La Serena, and Calama). Although a good study was provided, the following flaw has cast doubt on the findings: the study ignored the effect of temperature when calculating soiling losses based on the disparity of PV yield. There are so many irregularities in cleaning approaches as high personnel rotation was involved, where each cleaner uses a different cleaning pattern. The research highlighted significant uncertainty due to a weaker correlation between AOD and the soiling rate. The experiment ignored the influence of tilt angle and exposed module on a fixed angle based on a site's latitude, and previous studies [25, 26] reported a 10% variation caused by the influence of angular positioning. The soiling rate data presented was not spatially distributed; instead, a distinct value was illustrated for the region, with no interpolation estimates for various sites. The monthly soiling losses variation was calculated using the same results, which could lead to estimation errors of PV yield in the findings [25, 26] published.

Tanaka and Chiba [27] reported that Northern and West Africa are the regions with the most significant atmospheric dust loading rate across the globe, and Nigeria happens to be one of the regions. As previously mentioned, an enormous amount of work has been carried out in the field of soiling on PV, but this region (Nigeria) has received significantly less attention in recent years. However, some areas with high solar energy potential, low PV penetration and high energy deficiency (a wide gap between demand and supply), such as Nigeria, are still far behind in meeting up the sustainable development goal 7 (affordable, reliable and clean energy for all). The World Bank [28] highlighted a massive energy deficit where it was showing that Nigeria will have a population of 206 million in 2020, with only about 60% having access to energy that is unreliable and unsteady. The International Energy Agency (IEA) [29] stated that Nigeria's Renewable Energy (RE) target is 30 GW with 5.3 GW solar mini-grid and 2.8 GW small, medium scale (SMS) by 2030, but less than 10 MW PV installation was recorded in 2020.

Despite the reports presented above, it is notable that only a few studies [23, 30] considered multiple sites for data collection in their research. The literature showed results variation from studies conducted in the same region, which supports the claim that dust accumulation is location-dependent and the soiling rate of each region varies and should therefore be determined. In addition, when conducting an extensive literature review, it was observed that most soiling losses were recorded in a single location, during a particular season or few weeks-months, while ignoring seasonality and more extended exposure duration variation makes it extremely difficult to know the soiling rate of a country or region. It was also observed that some of these studies position coupons or PV modules on a single angle, limiting their analysis and prediction level. Similarly, it was observed that disregarding influencing factors could lead to inaccuracy of estimations. There has been an increased recognition that more attention is needed to be put on PV soiling in various regions with high solar energy potential and less PV penetration to scale up the application of renewable energy (RE) technology and reduce the gas emission that promotes climate change. Therefore, deploying multiple sensors or installing soiling stations over a more extended period could acquire temporal soiling variations and spatial data to provide more accurate estimations.

Nigeria is a strategic region with a high energy deficit and substantial solar energy potential, but its proximity to the source of Saharan dust is a concern to the performance of PV technology when deployed [2]. This study investigated the effect of soiling on PV performance, focusing on environmental variability as an influencing factor through developing a very simple, low-cost soiling station that collects optical losses data to generate a PV soiling losses map without installing a photovoltaic system. The concept provided is not only limited to the region of study; it could be replicated elsewhere and could also be used for large scale PV soiling predictions in the region, elsewhere, or in global scenarios. Different locations and their relative angular soiling losses are

investigated to accommodate other PV installation applications such as BIPV (Building Integrated PV), VIPV (Vehicle Integrated PV), and exterior/interior decorations operating on varying angular axes. The data provided could be used as a tool to help mitigate soiling effects on new PV installations in Nigeria. Indeed, it can be used to estimate the impact of soiling and optimise the operations and maintenance cycles even before PV plants are operational. The information provided in this report is not only limited to the solar energy industry but could entice potential readers and citations from the glass, financial, chemical, mechanical and mining industries. The soiling map is compared with a map published on the GSA website for validation, presenting variations. The study's secondary objectives are to examine the accumulated dust samples through elementology and mineralogy studies to identify their minerals, including each diaphaneity. The morphological characterisation was also conducted to categorise the regional depositions on the coupons, which was correlated with the air quality index (AQI). Optical losses and weather parameters were correlated for analysis purposes to determine the cause of accumulation on coupons and seasonality with significant concerns.

2 Method

Soiling in Nigeria was investigated using low iron glass coupons across geopolitical zones in the country. A simple in-house low-cost research jig was designed using solid works and fabricated with a 3D printer (Stratasys uPrint SE 3D printer) using an ABS (Acrylonitrile Butadiene Styrene) P430XL material. This research jig was selected after an initial comparative durability test using ABS, polylactic acid (PLA), wooden, and metallic material since it was intended to be exposed under harsh environmental conditions. Results show a high chance of particles moving onto the surfaces of coupons from wood and rusted metal during extreme weather conditions, while the PLA failed and bent when left in hot water (60°) over the period of two days. The ABS material has excellent thermal characteristics and remains stable at temperatures between -20° to 80°C. The same material was used to produce the transportation crates that reduce the shaking of coupons that could cause the removal of accumulated dust from coupons' surfaces and prevent sample breakage. Each crate was examined after transport to check if the particles were removed from the coupon during transport, but surprisingly the majority of the crates were found to be clean, and the unclear ones could not substantiate any findings.

About 315 pieces of 50 mm x 50 mm x 4 mm coupons of low iron glasses were distributed in the six geopolitical zones (North-Central, North East, Northwest, South East, South-south (Niger-Delta), and South-West) and the main base of data collection (Kaduna). A more detailed description and illustrations of the sites, set-up, transportation crates, installation, and sketches are presented in Fig. 1. Each station has three holders (one for monthly, one for seasonal and one for annual coupons), and each holder has three slots (one for vertical, one for tilt and one for horizontal) for exposing coupons to outdoor weather conditions. Angular optical soiling was investigated in this study to provide losses data consideration positioning variation that could be used for correction when PV technologies are deployed for various 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. Some of these applications allow the positioning of PV absorbing surfaces at a location-specific optimum angle, while others do not allow it due to their kind of application. In addition, some PV assets are sometimes deployed with solar single/dual-axis tracking technology that makes it follow the sun throughout the day, making the technology encounter dust accumulation at varying angular positions. The angular optical losses data could provide estimations that could be used for maintenance planning.

The distribution of coupons in various locations across the country is shown in Fig. 1 Table 2. Soiling stations with coordinates, fixed optimum angular PV positioning with the recorded Mineral and their transparency characteristics, and the AQI/PM data obtained from Air Plum Lab. Monthly coupons are exposed on the first day of the month, and then the coupon will be removed and replaced with a new clean coupon on the first day of the following month. Seasonal coupons were installed at the beginning of September when the research started to assume the wet season was coming to an end and marked the dry season's outset. Seasonal coupons were removed and replaced according to specific locations' seasons. Annual coupons were exposed at the end of the year and allowed to last for 12 calendar months before they were removed. All exposed coupons were sealed in special crates fabricated using the

above-mentioned 3D printer and transported back to the solar laboratory at the University of Exeter for detailed characterisation.

Table 1: Coupons dimension and distribution across all stations

Coupons (Low Iron Glass)		
Length	50 mm	
Height	50 mm	
Thickness	4 mm	
Monthly	3 coupons x 7 sites x 12 months	252
Seasonal	3 coupons x 7 sites x 2 seasons	42
Annual	3 coupons x 7 sites x 1 year	21
TOTAL		315

Coupons: 3 (Vertical, Horizontal and Tilt)
Seasons: 2 (Dry and Raining)
Sites: 6 Geopolitical Zones and main base
(see Fig. 1)

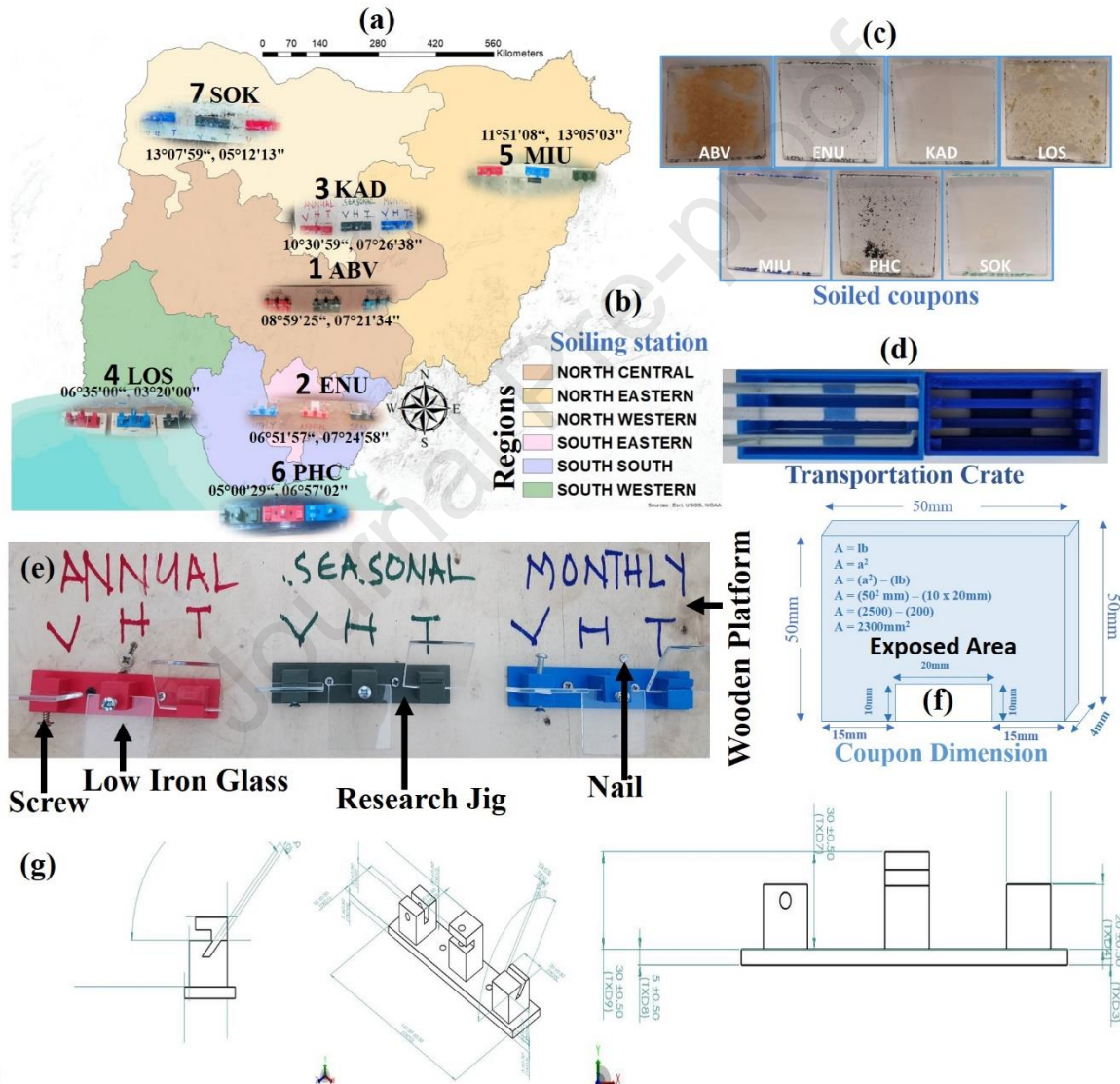
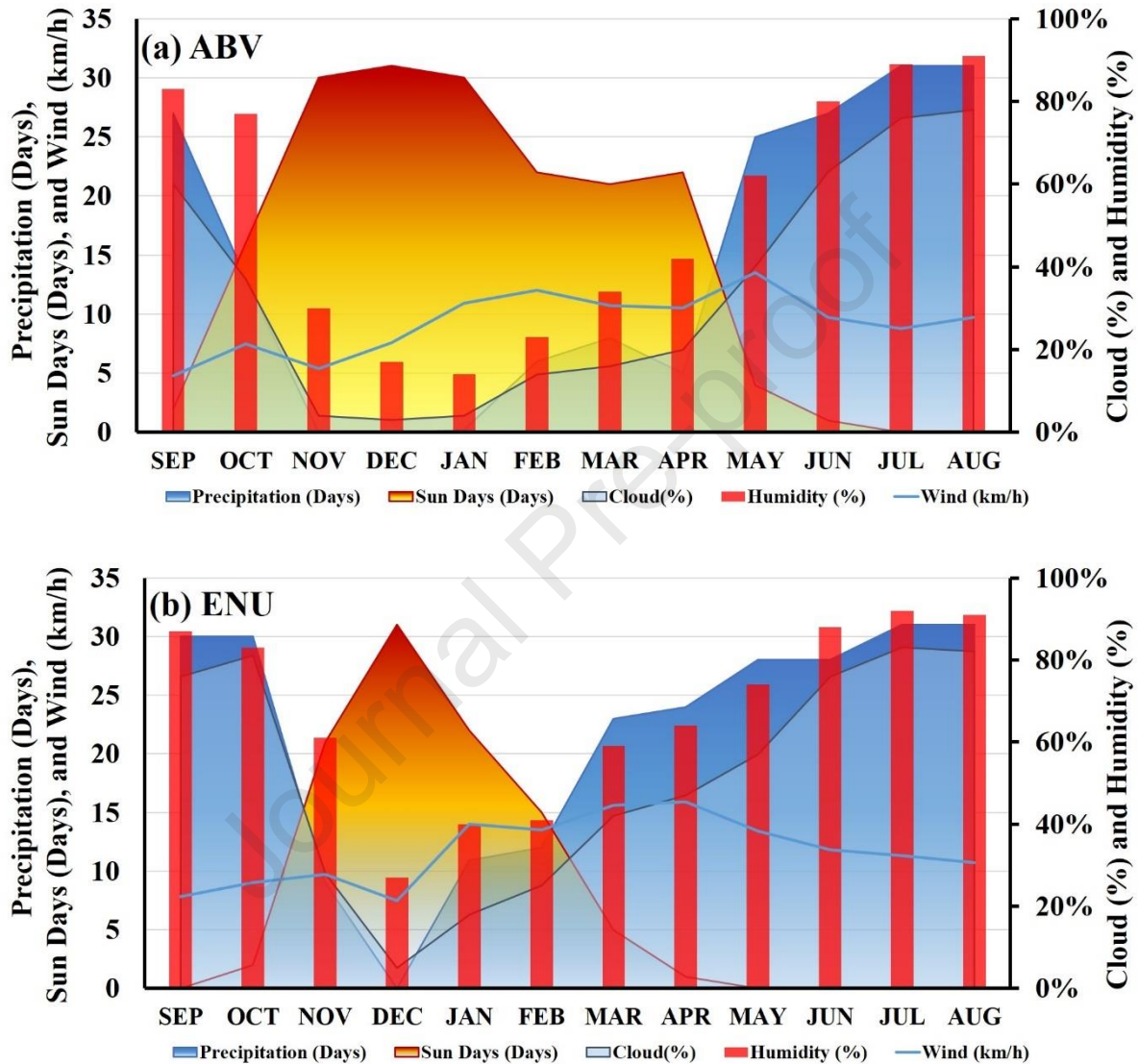


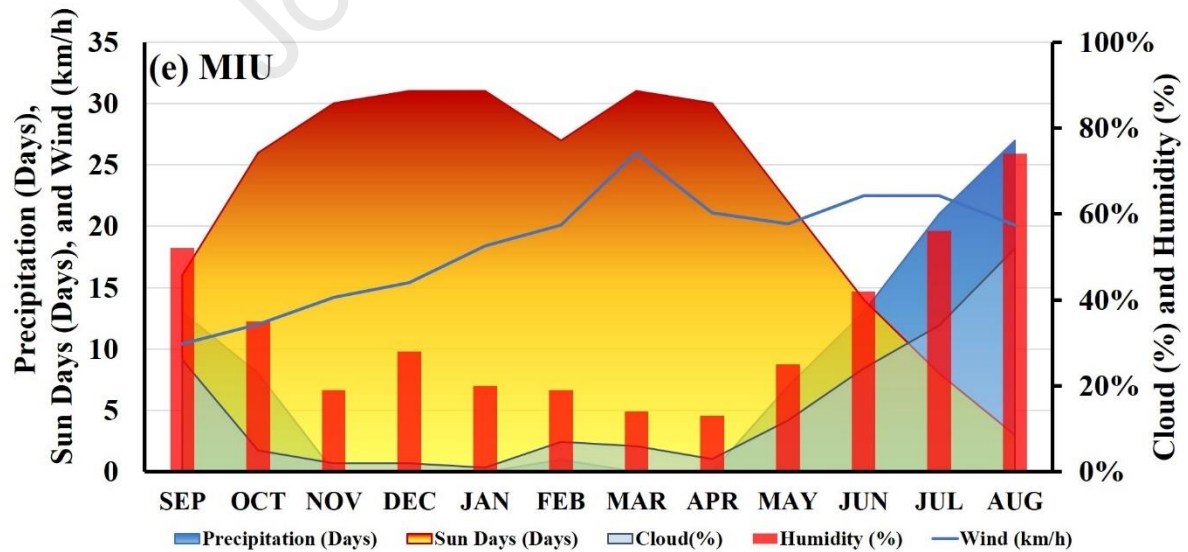
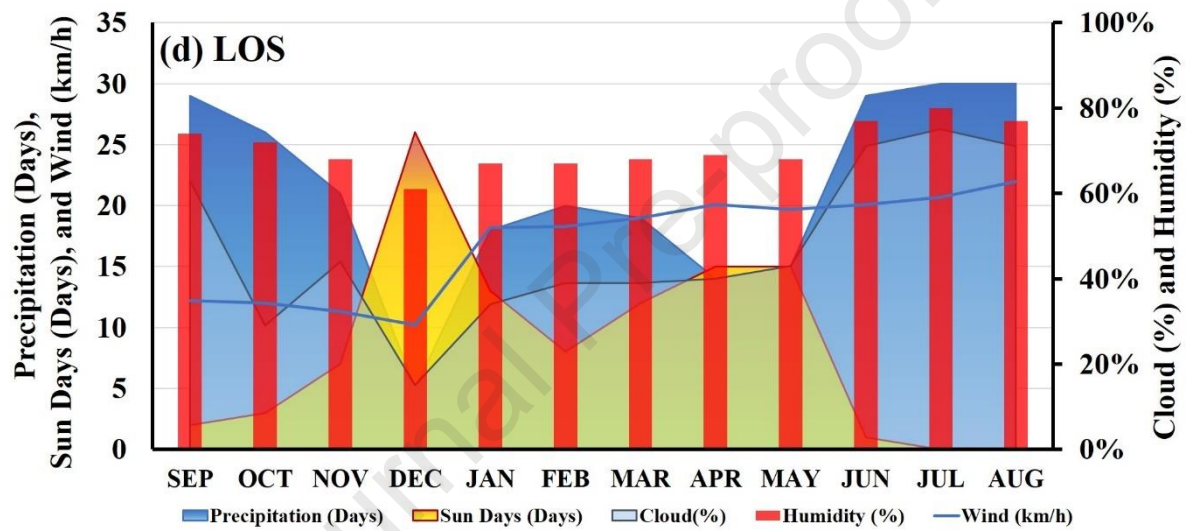
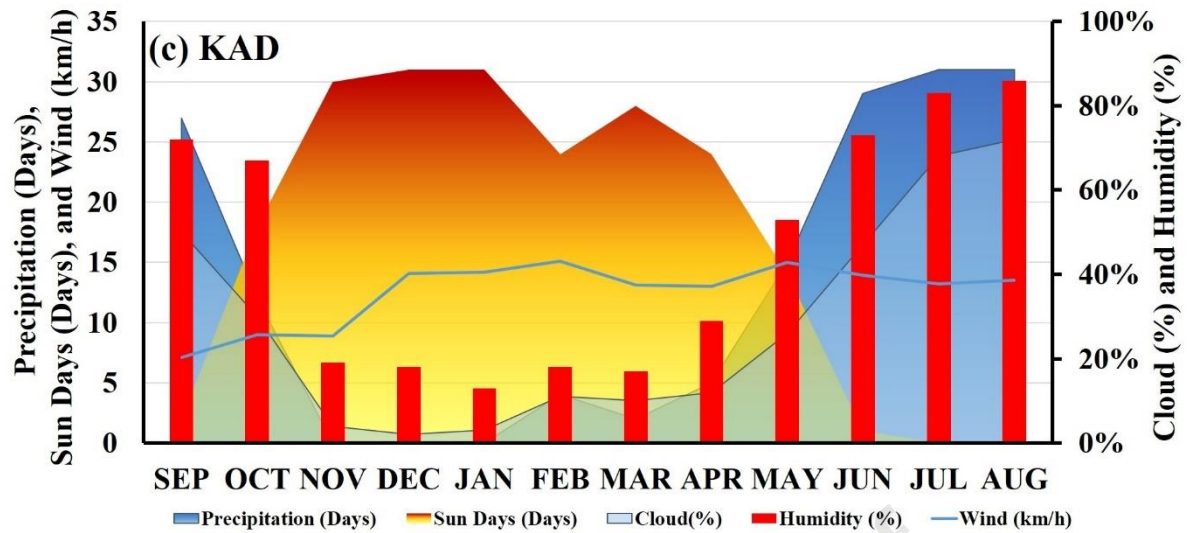
Fig. 1. Soiling station set-up and parameters, illustration (a) Map of Nigeria showing various soiling stations and their coordinates, (b) regions of soiling station as illustrated on the map, (c) soiled coupons samples, (d) transportation crate accommodating three samples with its cover, (e) typical soiling station set-up, (f) coupon dimension, and (g) sketch of deployed research jig.

Javed et al. [31] reported that wind speed and humidity are the two most interactive variables that determine the rate at which airborne dust particles settle on a platform. The soiling stations' sites provide monthly average weather data (precipitation, sunny days, cloud, humidity, wind, and visibility)

of the soiling stations sites are also provided in Fig. 2, used for analysis purposes in this report. The weather data showed periods when the dry, dusty weather condition occurred and periods when precipitation (mainly rainfall) happened, which can sometimes assist in removing or reducing the accumulated dust.

The influence of wind was minimised by installing all soiling stations in a pattern where coupons are forward-facing to each region's dominant incoming wind direction. This allows similarity of data collection across sites.





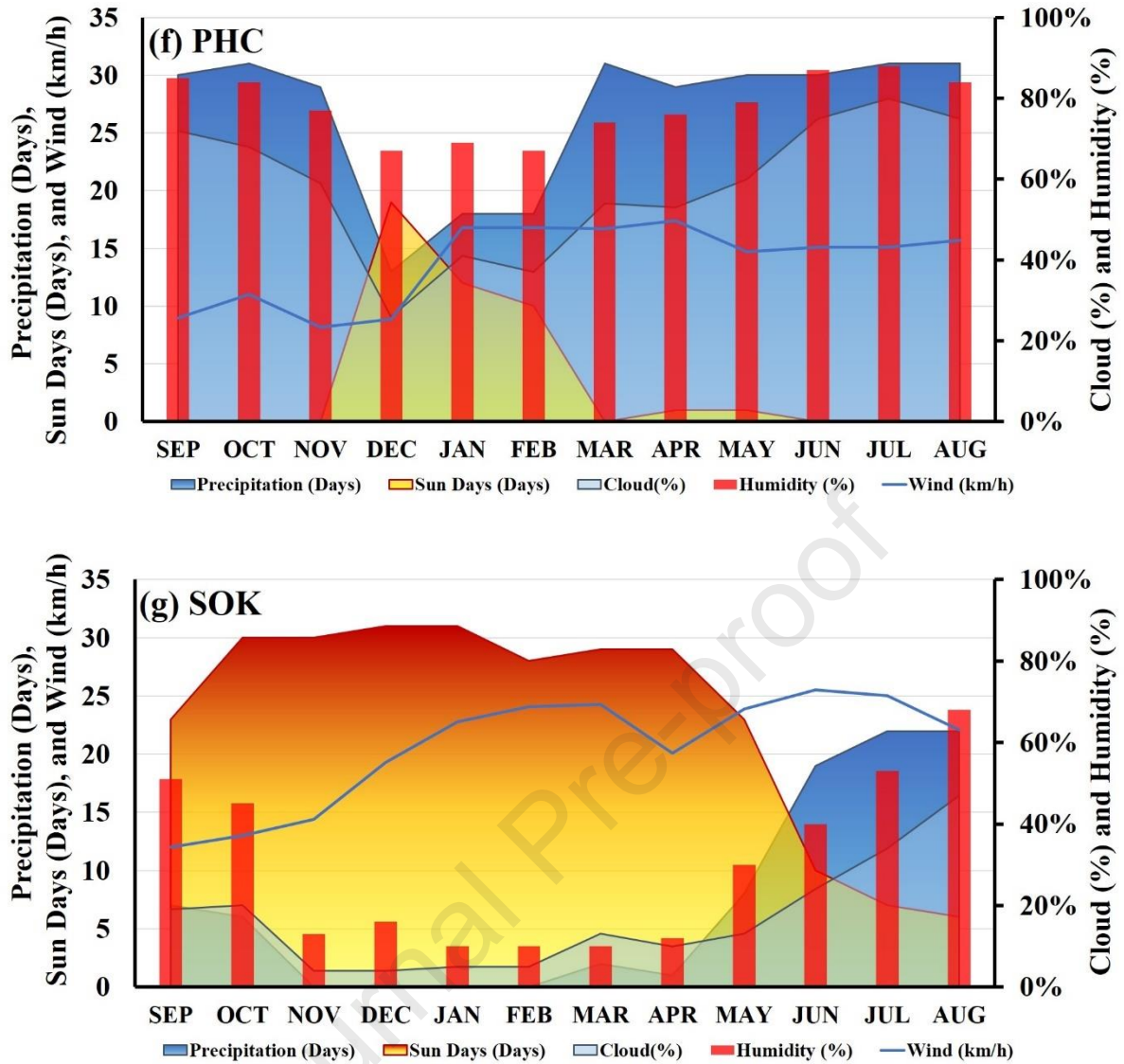


Fig. 2: Monthly weather information variation for soiling stations illustrating precipitation, wind speed, sun days/month, relative humidity, and cloud (weather data obtained from World Weather Online[32]) for (a) – Abuja, (b) – Enugu, (c) – Kaduna, (d) – Lagos, (e) – Maiduguri, (f) – Portharcourt, and (g) – Sokoto.

2.1 Optical characterisation procedure

The spectral characterisation was conducted to define the transparency level of the accumulated dust particles on the various coupons. This experiment was conducted when samples were brought back to the University of Exeter laboratory. Perkin Elmer Lambda 1050 UV/VIS/NIR spectrophotometer examined each exposed coupon. A clean coupon was usually examined at the beginning of every test to benchmark the optimum transmittance level that could be achieved. Afterwards, each sample was then subjected to a transmittance measurement. NIR (Near Infra-Red), VIS (Visual) and UV (Ultraviolet) transmittance levels of each coupon are examined, ranging from 300 nm to 1100 nm wavelength. This range of wavelength is considered to be accommodating all the different PV technologies (solar cells) available in the market as they respond only within this spectrum. Results obtained in this experiment were validated using Equation (1) below, where $S(\lambda)$ is the relative solar radiation wavelength distribution, $\Delta\lambda$ is the change in wavelength, and $T(\lambda)$ is the spectral transmittance.

$$\tau_{solar} = \frac{\sum_{\lambda=300nm}^{1100nm} S(\lambda)T(\lambda)\Delta\lambda}{\sum_{\lambda=300nm}^{1100nm} S(\lambda)\Delta\lambda} \quad (1)$$

Transmittance losses were calculated using Equation (2) below, and the extreme optical loss results were used instead of average to accommodate a possible worst-case scenario. The results are presented in percentage reduction, where τ_{clean} is the transmittance data of clean coupons and τ_x is the transmittance data of an exposed coupon on a certain angle.

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

This Equation (2) provided data employed in obtaining the power reduction of a kWp installation due to soiling. A simple approach to determining soiling losses, where reduction is determined by multiplying PV yield of kWp by the factor of (1-loss), where the loss refers to the percentage change in optical transmission obtained by employing Equation (2). This approach with simplicity would allow repeatability in other regions to determine soiling loss value.

2.2 Particle characterisation

The sample particle characterisation was conducted to determine the chemical composition of dust particles in various soiling stations. One coupon with a high accumulation from the various soiling stations was carefully selected and exposed to imaging characterisation. Each sample was initially prepared with carbon coating using an Emi-Tech K950 device before being subjected to microscopic scanning. The SEM (S) Quanta FEG 650 was employed to generate the secondary electron (SE) image and backscattered electrons (BSE) image that was used for further mineral data acquisition using the EDX (Energy Dispersive X-ray). The EDX generated graphs highlighting mineral element's samples and their content level, which helped identify the various minerals' chemical composition. Minerals and their morphological characteristics such as diaphaneity were identified using online minerals databases such as minerals.net, mindat.org and webminerals.com.

Additional information regarding the air quality of various regions in Nigeria was obtained from the Air Plume lab. The data were required for in-depth analysis of suspended particles in the atmosphere across the various regions. Air quality data highlights the aerosol particles' categories used to analyse and validate the minerals recorded from the SEM/EDX imaging and analysis. Annual average AQI highlights the severity of the harmfulness of atmospheric particles to humans using an innovative standard developed by Air Plume Lab [33] with seven different levels to eliminate the variability of different standards and also align with the World Health Organisation (WHO) recommended threshold is presented in a map format in Supplementary Fig. 17. The number of days considering the severity of harmfulness of air quality in the various regions is illustrated in Supplementary Fig. 18.

2.3 Soiling mapping procedure

This is an approach for presenting PV soiling data. The coupon's transmittance data was collected from optical characterisation through spectral measurement using a spectrometer, as mentioned in section 2.1 of this paper. PV output and direct normal irradiance data were collected from Global Solar Atlas, considering the small residential capacity of 1kWp. These data were used in calculating soiling losses, and the results were presented innovatively for easy understanding and further application. Linear interpolation was employed to determine the optical transmittance degradation of each soiling site's optimum PV tilt angle since coupons were not positioned at that angle. This interpolation technique was considered since it could establish a data point whenever established discrete data points, where $\Delta\tau_{(Optimum)}$ is the calculated change of transmittance of a coupon at an optimum angle, $\beta_{(x)}$ is the optimum tilt angle of a particular station, $\beta_{(45)}$ is the tilt angle described as tilt angle in this research where coupons are positioned as tilt which is 45° , $\beta_{(0)}$ is the horizontal angle at which a coupon is positioned on the research jig in soiling stations, $\Delta\tau_{(0)}$ is the optical loss recorded on a coupon positioned on a horizontal plane, and $\Delta\tau_{(45)}$ is the optical loss recorded on the coupon positioned on the tilt angle plane (45°).

$$\Delta_{\tau_{(Optimum)}} = \frac{(\beta_{(x)} - \beta_{(45)}) (\Delta_{\tau_{(0)}} - \Delta_{\tau_{(45)}})}{(\beta_{(0)} - \beta_{(45)})} + \Delta_{\tau_{(45)}} \quad (3)$$

ArcMap 10.6.1 from ArcGIS was employed to design the soiling map using the PV output and soiling losses data. An interpolation method called Kriging interpolation was employed, based on Equation (4) below Venkatramanan et al. [34] provided. The Kriging interpolation is a geostatistical method that provides smooth estimates to determine an unknown spatial value of a location. Venkatramanan et al. [34] defined Kriging interpolation as the best technique for unbiased linear estimation of unknown spatial values and temporal variables, where Z_K^* is the smooth estimate produced by Kriging interpolation, λ_i is the weight for Z_i , which is to ensure unbiasedness of the estimation, and Z_i is the variable.

$$Z_K^* = \sum_{i=1}^n \lambda_i Z_i \quad (4)$$

Equation (5), provided by Venkatramanan et al. [34], represents the unbiased condition of kriging interpolation, where Z_V is the actual value and the Z_K^* is the calculated estimated value, which is:

$$E \{Z_V - Z_K^*\} = 0 \quad (5)$$

Equation (6), provided by Venkatramanan et al. [34], shows the summation of the weight (λ_i) which is:

$$\sum_{i=1}^n \lambda_i = 1.0 \quad (6)$$

Equation (7), provided by Venkatramanan et al. [34], shows the estimation variance of Kriging interpolation, where $\bar{C}(V, V)$ is the covariance between the variables of the samples, μ is the Lagrange parameter, $\bar{C}(v_i, V)$ is the covariance between the estimations and the variables of the samples, which is:

$$\sigma_K^2 = E \{[Z_V - Z_K^*]^2\} = \bar{C}(V, V) + \mu - \sum_{i=1}^n \lambda_i \bar{C}(v_i, V) \quad (7)$$

Equation (7) is provided to explain how the errors are reduced when estimating the values of Equation (5), which is a further description of the Kriging interpolation equation provided above in Equation (4).

The calculated soiling losses variation presented in Fig. 6 provided the disparity between the result obtained from this study and the GSA PV yield using a constant value of 4.5% data. The difference between the two values is that higher disparities were observed with increased soiling losses value. It also increases with time since more irradiance is available to generate PV yield, and the 4.5% soiling losses constant would not change with time. Therefore, it will create a broader gap of soiling losses as the duration increases, and soiling losses increase due to a significant amount of irradiance that was not converted to useful energy.

ArcMap from ArcGIS is a software that provides the platform to present geographic information in layers and could be used to perform a wide range of GIS-related tasks, including compilation, organisation, and modification of GIS datasets, use of geoprocessing for analytical and visual purposes [18]. The application is mainly used by government administrative established compared with MapBox, leaflet, and Google and has the highest market share in the mapping application industry [19]. This application was employed in this study because it provides flexibility to create and edit datasets. The application is secured and requires a license for online access that allows users to load required real-world geographical information data [20]. Three software (ArcGIS, MapBox, and Tableau) were

employed to develop the mapping, but the result was better achieved using ArcGIS because of the advanced inbuilt tools that support the modification of datasets.

The Kriging interpolation technique is an advanced geostatistical approach that generates an estimated surface from a given scattered set of points with z-values [21]. This technique uses an interactive investigation of the spatial behaviour of the inputted data to select an excellent estimation for output generation. Desktop.ArcGIS [21] provided a multistep process for Kriging interpolation, including exploratory statistical data analysis, variogram spatial structural modelling, creating the surface, and exploring surface variation. The main dissimilarity with other spatial interpolation techniques in ArcGIS, such as the inverse distance weighted (IDW) and Spline interpolation, is that it is not a deterministic approach based on surrounding values but a geostatistical approach that is based on a statistical model which includes autocorrelation, where it could produce a significant measure of accuracy during predictions [21]. Krishnan and Ganguli [22] reported that the Kriging interpolation model could provide higher accuracy and lower computational cost for predicting distribution spatial frequencies compared to other deterministic techniques. Zhang et al. [23] reported that kriging model fitting accuracy could reach up to 0.980. Fischer et al. [24] supported this claim by examining three interpolation techniques (inverse distance weighted, ordinary Kriging, and Empirical Bayesian Kriging), and the ordinary Kriging consistently yielded more accurate results than others. The technique assumes the distance of sample points reflects spatial correlation to explain surface variance. It uses all points provided to generate output in a specified radius using a mathematical function of unbiasedness [18]. Based on this literature and a comparative assessment using the GSA map and its data (direct normal irradiance and PV performance with 4.5% soiling rate), the accuracy of IDW and Kriging were investigated, and our finding shows that Kriging interpolation provides better map output than is more similar to the GSA map. As such, the technique was employed for generating soiling maps.

This novel approach is motivated by recent progress made by GSA in providing solar energy information, which could be improved by adopting the method used in this study since it offered a low-cost soiling station that could be used to determine the actual regional soiling loss. The approach could stimulate further soiling research across the globe and reduce the inaccuracy reported. The paper contributes to the body of knowledge with the unique, low-cost approach used to determine the soiling rate, which policymakers can use, PV companies, researchers, and potential PV investors. The findings from this study may lead to a better understanding of soiling problems since the work highlights the significance of the effect of soiling, considering environmental differences as an influencing factor. The findings provided more accurate and realistic soiling information for better PV installation and maintenance planning to achieve higher yields.

3 Results

The spectrophotometer was employed to measure the transmittance losses on coupons, scanning electronic microscope/ energy dispersive X-ray (SEM/EDX) was used to determine the soiled particles' chemical composition ArcGis (ArcMap 10.6.1) was employed to develop a soiling losses map. All the results are illustrated in this section.

3.1 Optical transmittance losses

The optical losses results are grouped by exposure period, and each group is further divided into subgroups based on their positioning angles. This illustrates transmittance losses of various locations at a glance for better understanding. Graph plots illustrating relative optical losses variation relative to wavelengths of all exposed coupons are provided in the supplementary figures section from Supplementary Fig. 1 to Supplementary Fig 15. Below charts were provided to highlight relative changes.

Fig. 3 (a) illustrates the annual transmittance loss results. The most significant loss of about 59% was recorded on the Abuja (ABV - 08°59'25", 07°21'34") coupon that was positioned on a horizontal plane, while the lowest loss was about 3% and was recorded on the Maiduguri (MIU - 11°51'08", 13°05'03") coupon that was positioned at a vertical angle. Fig. 3 (b) illustrates the dry season transmittance loss results where the 88% loss was recorded for the horizontally placed ABV coupon, while the lowest loss is about 4% from the vertically placed Enugu (ENU - 06°51'57", 07°24'58") coupon. On the other hand,

Fig. 3 (b) illustrated wet season transmittance losses, and the most significant losses were recorded from Lagos (LOS - 06°35'00", 03°20'00") and Port Harcourt (PHC - 05°00'29", 06°57'02") coupons positioned on horizontal planes, with the first having about 55% reduction and the latter having about 45%. The lowest transmittance losses for the wet season were recorded from Kaduna (KAD - 10°30'59", 07°26'38") and MIU coupons, with both having about a 3% reduction when coupons were positioned vertically. Sokoto (SOK - 13°07'59", 05°12'13") coupons appear average in all positions.

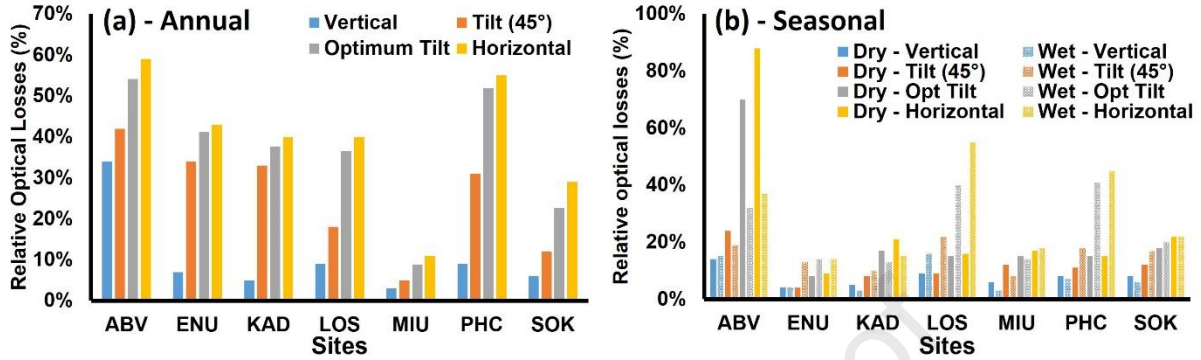


Fig. 3. (a) Annual optical transmittance losses variation for vertical, 45° tilt, and horizontal orientation. At the same time, (b) illustrates seasonal optical transmittance losses variation for vertical, 45° tilt, and horizontal orientation, with Dry highlighting dry seasonal variations and Wet showing wet seasonal variations for the seven regions.

Fig. 4 (a) illustrates monthly results from coupons that are vertically positioned, with the lowest optical losses of about 1% in September (for ABV, ENU, and LOS), October (for ENU and KAD), and November (SOK). Fig. 4 (a) further illustrates the optical loss recorded for the vertically positioned coupons, with a maximum of 10% in January (for ABV). Fig. 4 (b) illustrates results from coupons that are positioned at 45° tilt, with the lowest optical losses of about 2% in September (ENU and LOS), October (for KAD), and February (LOS). Fig. 4 (b) further illustrates the maximum loss for the 45° tilt position, with about 19% in December (for LOS). Fig. 4 (c) illustrates optical loss results of each site's optimum tilt calculated from the interpolation between horizontal and 45° tilt relative transmittance reductions, with the lowest optical loss of about 2% in September (for ENU and LOS). Fig. 4 (c) further illustrates the maximum loss for the optimum tilt angle position, with about 29% in February (for ABV). Fig. 4 (d) illustrates results from horizontally positioned coupons, with the lowest optical losses of about 2% in September (ENU and LOS). Fig. 4 (d) further illustrates the maximum loss for the horizontal position, with about 38% in January (for ABV).

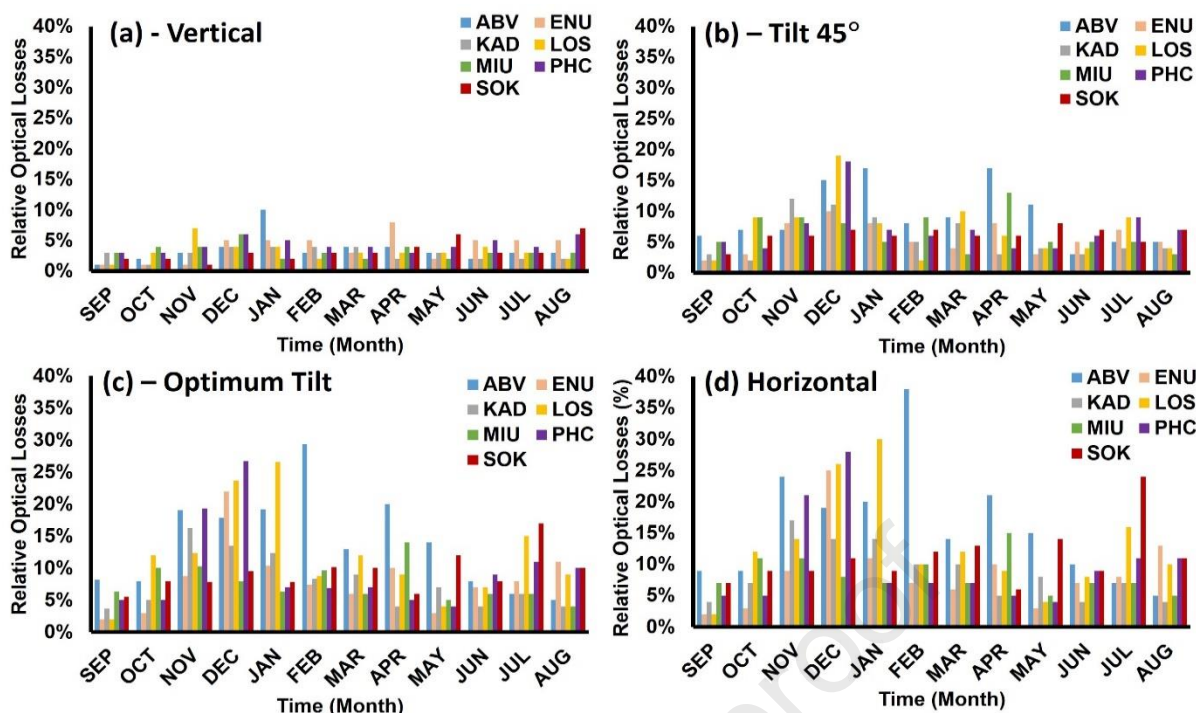


Fig. 4. Variation of monthly optical transmittance losses in relation to the angular position of coupon with respect to the terrain as the reference point (=0); where (a) Vertical (90°), (b) Tilt (45°), (c) optimum tilt angle for the exposure site, and (d) horizontal (0°). (a) illustrates higher accumulation was recorded in January (on the ABV coupon), and most minor were recorded in September (on ABV, ENU, and LOS coupon), October (ENU and KAD coupon) and November (SOK and ENU coupon) for the vertically positioned coupons. (b) shows the most increase was recorded in December (on the LOS coupon), and the most minor were recorded in September (on ENU and LOS coupon), October (on KAD coupon) and February (LOS) for 45° positioned coupons. (c) depicts the calculated optical losses value with the most significant accumulation recorded in February (on the ABV coupon), and the most minor were recorded in September (on KAD and LOS coupons) for coupons positioned at a site-specific optimal angle. (d) demonstrates that the most significant accumulation was recorded in February (on the ABV coupon), and the most minor were recorded in September (on ABV) for horizontally positioned coupons.

3.2 Particle characterisation

This section presents the results of the SEM/EDX scanings. SEM images of particle samples with their various locations, highlighting the sizes and spaces they occupied on the coupons, are provided in Supplementary Fig. 16. However, the backscattered electron images (BSE) were employed for in-depth analysis to determine the mineral composition using EDX. Data obtained from the EDX analysis were employed to identify the essential mineral and their characteristics using the online mineral data databases such as minerals.net, mindat.org and webminerals.com.

A critical property (diaphaneity) of each identified mineral was investigated, and some of the minerals possess a characteristic that would negatively affect light transmittance. Table 2 highlights some minerals that were repeatedly identified during the particle characterisation. The results from the Northern region show the diaphaneity property of some of the minerals where the coupons from North-East appear to be translucent and opaque, and coupons from North-Central possess minerals found to have translucent and opaque properties. In contrast, the coupons from North-West appears to have minerals with both transparent and translucent property. In the Southern region, Table 2 shows that the coupon from the South-East possesses minerals that appear to be transparent, translucent, and some are opaque. The particles on the South-South coupon have minerals with opaque properties, while the minerals identified on the South-West coupon possess translucent and opaque transparency properties. Table 2. illustrates the Air Quality Index (AQI) of various regions and the main pollutants.

Table 2. Soiling stations with coordinates, fixed optimum angular PV positioning with the recorded Mineral and their transparency characteristics, and the AQI/PM data obtained from Air Plum Lab.

S/N	Location Region Latitude Longitude Optimum PV Tilt Angle (OPTA)	Minerals	Diaphaneity	Annual Average Best day Worst day	Main Pollutant	
					AQI	$\mu\text{g}/\text{m}^3$
1.	ABV (Abuja) North Central 08°59'25" 07°21'34" OPTA - 13°	Chlorite (Chamosite)	Translucent to sub-translucent	75 AQI Best – 17 AQI Worst – 330 AQI	PM ₁₀ – 343.7	PM ₁₀ – 469.9
		Montmorillonite	Translucent to Opaque		PM _{2.5} – 399.8	PM _{2.5} – 349.8
		Pyroxene (Spodumene)	Transparent to Translucent		SO ₂ – 6.6 CO – 9.98 O ₃ – 111.6 NO ₂ – 19.3	SO ₂ – 6.6 CO – 1997.8 O ₃ – 178.5 NO ₂ – 38.6
2.	ENU (Enugu) South East 06°51'57" 07°24'58" OPTA - 10°	Tourmaline (Dravite)	Translucent to opaque	75 AQI Best – 16 AQI Worst – 399 AQI	PM ₁₀ – 450.7	PM ₁₀ – 641.1
		Analcite	Translucent		PM _{2.5} – 524.9	PM _{2.5} – 474.9
		Pectolite	Transparent to Translucent		SO ₂ – 21.1 CO – 22.2 O ₃ – 111.6 NO ₂ – 46.7	SO ₂ – 24.0 CO – 4398.1 O ₃ – 178.5 NO ₂ – 75.5
3.	KAD (Kaduna) North West Main Base 10°30'59" 07°26'38" OPTA - 15°	Tourmaline	Translucent to opaque	96 AQI Best – 22 AQI Worst – 388 AQI	PM ₁₀ – 415.8	PM ₁₀ – 585.3
		Chlorite (chamosite)	Translucent to sub-translucent		PM _{2.5} – 394.7	PM _{2.5} – 344.7
		Garnet (almandine)	Transparent to Translucent		SO ₂ – 32.1 CO – 15.9 O ₃ – 94.6 NO ₂ – 26.9	SO ₂ – 62.5 CO – 3181.8 O ₃ – 153.5 NO ₂ – 49.2
4.	LOS (Lagos) South West 06°35'00" 03°20'00" OPTA - 7°	Stilpnomelane	Subtranslucent to opaque	65 AQI Best – 14 AQI Worst – 392 AQI	PM ₁₀ – 322.3	PM ₁₀ – 435.7
		Beryl	Transparent to subtranslucent		PM _{2.5} – 336.4	PM _{2.5} – 286.4
		Amphibole	Translucent to Subopaque		SO ₂ – 51.97 CO – 72.1 O ₃ – 170.96 NO ₂ – 73.7	SO ₂ – 133.9 CO – 8278.8 O ₃ – 273.5 NO ₂ – 136.9
5.	MIU (Maiduguri) North East 11°51'08" 13°05'03" OPTA - 17°	Zeolite (Clinoptilolite)	Transparent	117 AQI Best – 21 AQI Worst – 562 AQI	PM ₁₀ – 362.9	PM ₁₀ – 500.5801
		Ilmenite	Opaque		PM _{2.5} – 455.6	PM _{2.5} – 405.5584
		Illite	Translucent		SO ₂ – 12.6 CO – 8.9 O ₃ – 90.8 NO ₂ – 19.4	SO ₂ – 12.57944 CO – 1783.942 O ₃ – 148.9783 NO ₂ – 38.81303
6.	PHC (Port Harcourt) South-South 05°00'29" 06°57'02" OPTA - 6°	Felspar (albite)	Transparent, Translucent	62 AQI Best – 13 AQI Worst – 321 AQI	PM ₁₀ – 322.2	PM ₁₀ – 435.555
		Schorlomite	Opaque		PM _{2.5} – 367.1	PM _{2.5} – 316.4977
		Scapolite	Translucent to Opaque		SO ₂ – 32.5 CO – 17.7 O ₃ – 122.8 NO ₂ – 41.4	SO ₂ – 63.86763 CO – 3546.805 O ₃ – 196.5006 NO ₂ – 68.52894
7.	SOK (Sokoto) North West 13°07'59" 05°12'13" OPTA - 17°	Chlorite (Chamosite)	Translucent to subtranslucent	95 AQI Best – 20 AQI Worst – 418 AQI	PM ₁₀ – 557.2	PM ₁₀ – 811.6
		Montmorillonite	Translucent to Opaque		PM _{2.5} – 369.7	PM _{2.5} – 319.7
		Feldspar (labradorite)	Translucent to transparent		SO ₂ – 14.1 CO – 12.3 O ₃ – 128.1 NO ₂ – 42.1	SO ₂ – 14.1 CO – 2453.1 O ₃ – 205.1 NO ₂ – 68.3

3.3 Soiling mapping

In combination with PV Output data obtained from the Global Solar Atlas, the transmittance losses were used to develop a new soiling losses map for Nigeria. Since the PV output collected from Global solar was based on the optimum angle of each location, a linear interpolation was employed to obtain optimum angle optical transmittance losses data, which is comprehensively explained in the methodology section of this paper. PV output data with and soiling losses are provided according to the timestamp for annual in Table 3, for the two seasons (dry and wet) in Table 4, and for various 12 calendar months in Table 5

The soiling maps are grouped based on the period of exposure, and each group includes a direct normal irradiance [16], PV output without soiling, and PV output at a fixed position based on the site's optimum PV tilt angle (provided in Table 1) with soiling based on the transmittance losses data presented above, and the PV output with a constant 4.5% soiling loss map [16]. This is employed to illustrate solar energy potential and the variation between the result of this study and the information provided on the Global Solar Atlas website.

Table 3. Estimated annual PV output with and without soiling losses for seven sites.

Annual PV output (kWh/kWp)		
STATE	Without Soiling	With Soiling
ABV	1506	691
ENU	1399	823
KAD	1623	1012
LOS	1299	824
MIU	1706	1555
PHC	1304	628
SOK	1695	1313

Fig. 5 (c) shows that the most significant soiling loss was recorded in North-Central, where the PV output degraded from about 1505.76 kWh/kWp to 691.3 kWh/kWp (54% loss), and the lowest loss was recorded in the North-East region where PV output decreased from 1705.76 kWh/kWp to about 1554.52 kWh/kWp (9% loss). In comparison, the maps presented in Fig 5 distinguish the variation between a constant soiling value (of 4.5 %) and actual soiling losses values for a wider region. The reader could easily observe a wider variation when comparing the values from the maps in Fig. 5 (b) and Fig. 5 (d), where an additional 50% loss was recorded for the North-Central region. Fig. 5 (d) illustrates that the greatest loss was recorded in the North-East region, where PV yield degraded from 1705.76 kWh/kWp to about 1629 kWh/kWp (4.5% loss), and the lowest reduction was in the South-West where the reduction was from 1299.48 kWh/kWp to about 1241 kWh/kWp (4.5% loss). Although the loss percentage is constant, it is observed that losses are greater in regions with higher potential. In comparison, the reader could easily observe a wider variation when comparing the values from the maps in Fig. 5 (b) and Fig. 5 (d), where an additional 25% loss was recorded for the North-Central region.

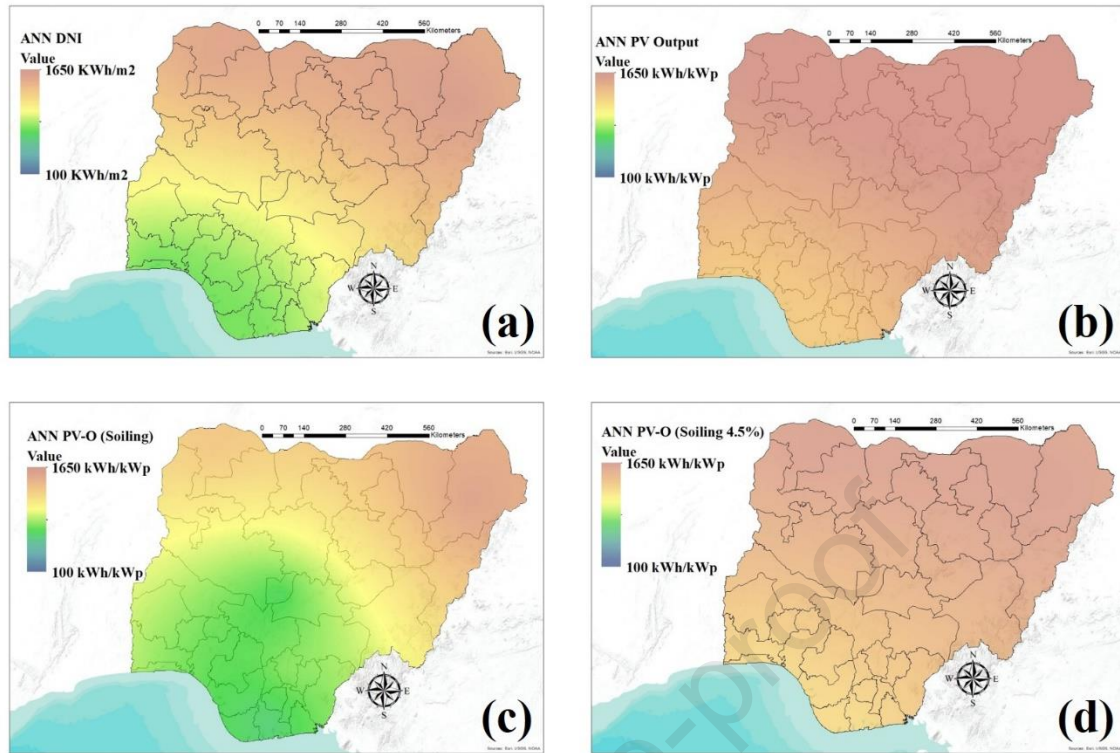


Fig. 5. Mapping annual regional variation of DNI (Direct Normal Irradiance) potential and PV output of Nigerian highlighting soiling losses disparity and showing significant soiling losses in the South-East, South-West, South-South, and North-Central with; (a) highlighting the annual solar energy potential of all the region in the country, (b) demonstrating the annual PV output potential with no soiling, (c) illustrating the annual soiling losses determined through optical losses, and (d) showing the annual PV output reduction due to constant soiling losses rate (4.5%).

Table 4. Estimated seasonal (dry and wet) PV output with and without soiling losses for seven sites.

STATE	Seasonal PV output (kWh/kWp)			
	DRY		WET	
	No Soiling	Soiling	No Soiling	Soiling
ABV	819	246	687	467
ENU	646	594	753	648
KAD	884	733	740	644
LOS	336	286	964	578
MIU	1064	904	641	551
PHC	241	205	1063	627
SOK	1041	853	655	524

The results of the seasonal soiling mapping show a significant variation in soiling losses during the two seasons across regions. Fig. 6 (c) illustrates the soiling losses in the dry season. It shows that in North-Central, the PV output decreased from about 818.53 kWh/kWp to 573.0 kWh/kWp (30% loss) and in the South-South from 240.6 kWh/kWp to about 204.5 kWh/kWp (14% loss). Fig. 6 (d) shows PV output reduction due to soiling losses where the most significant decrease was observed in the North-East region from 1064.1 kWh/kWp to about 1016.2 kWh/kWp (4.5% loss), and the lowest reduction was from South-South where the drop was from 240.6 kWh/kWp to about 229.8 kWh/kWp (4.5% loss). The approach used in the study presented a greater soiling value as shown in Fig. 6 (c), where about 245.53 kWh/kWp reduction is obtained in North-Central compared to reduction illustrated in Fig. 6 (d) which shows 36.8 kWh/kWp using 4.5% constant soiling value.

On the other hand, Fig. 7 (c) shows that the most significant soiling loss in the wet season was recorded in South-South, where the PV output decreased from about 1063.4 kWh/kWp to about 627.4 kWh/kWp (41% loss) and the lowest loss was recorded in the North-East region where PV output reduces from 641.3 kWh/kWp to about 551.5 kWh/kWp (14 % loss). Fig. 7 (d) shows the most significant reduction was recorded in the South-South region from 1063.4 kWh/kWp to about 1015.5 kWh/kWp (4.5% loss), and the lowest drop was from the North-East where the decrease was from 641.3 kWh/kWp to about 612.4 kWh/kWp (4.5% loss).

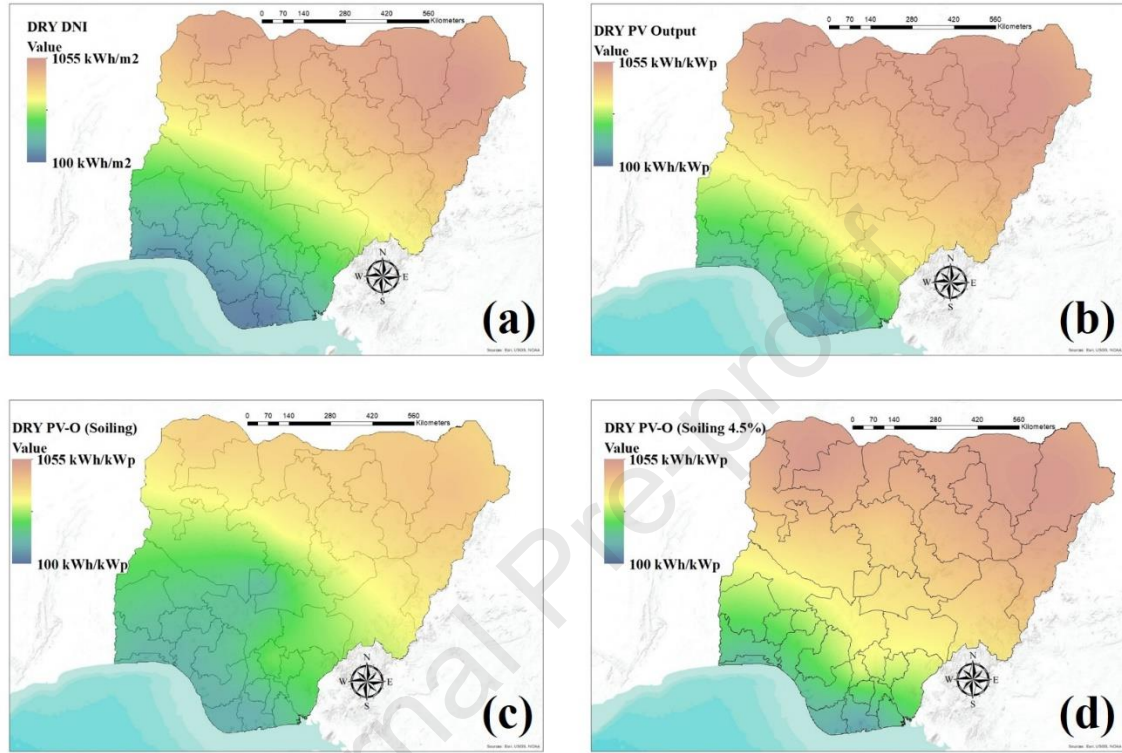


Fig. 6. Mapping dry season regional variation of DNI (Direct Normal Irradiance) and PV output potential of Nigeria, highlighting soiling losses disparity during the season; (a) illustrates solar energy potential for the dry season in the country, (b) shows PV output potential for the dry season without soiling, (c) illustrates the PV yield with soiling losses for the dry season, and (d) shows the dry season PV output with constant soiling losses rate (4.5%).

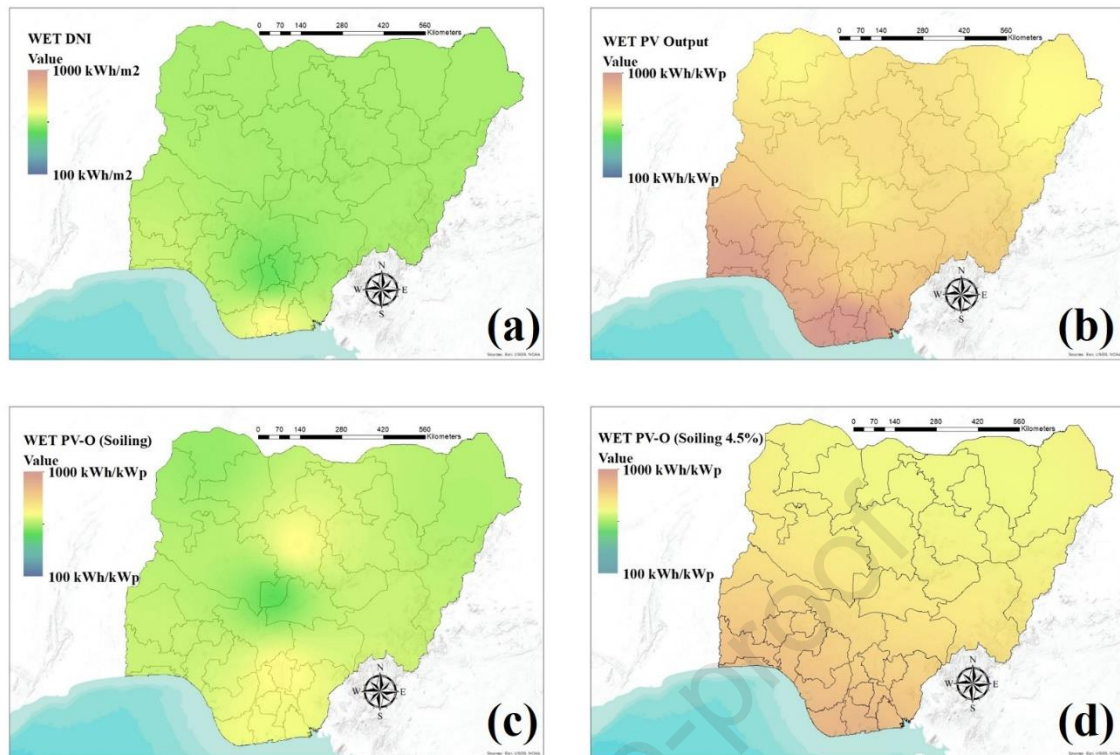


Fig. 7. Mapping wet season regional variation of DNI and PV output potential of Nigeria, highlighting soiling losses disparity with (a) highlighting solar energy potential for the wet season in the country, (b) demonstrating PV output potential for the wet season without soiling, (c) illustrating the PV yield with soiling losses for the wet season, and (d) showing the wet season PV output with constant soiling losses rate (4.5%).

The monthly result shows different values of soiling losses for each month. Consequently, the results are shown in monthly-based maps. All monthly maps are illustrated in Supplementary Fig. 19 to Supplementary Fig. 30. Table 5 provides the PV yield with and without soiling losses for the sites based on kWp installation.

Table 5. Estimated monthly PV output with and without soiling losses for seven sites.

STATE	PV output without soiling losses (kWh/kWp)											
	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
ABV	115	136	150	147	140	125	133	123	123	110	105	100
ENU	105	118	135	141	132	117	121	116	116	104	100	95
KAD	126	146	157	158	154	137	144	134	134	117	112	107
LOS	100	110	112	119	112	105	117	117	117	97	96	97
MIU	139	155	155	160	161	143	150	135	135	121	125	124
PHC	103	114	116	124	116	105	109	114	114	98	94	99
SOK	141	151	151	156	155	140	146	137	137	127	130	126
STATE	PV output with soiling losses(kWh/kWp)											
	SEP+S	OCT+S	NOV+S	DEC+S	JAN+S	FEB+S	MAR+S	APR+S	MAY+S	JUN+S	JUL+S	AUG+S
ABV	106	125	121	121	113	88	116	99	105	101	98	95
ENU	103	115	123	110	118	109	114	104	112	97	92	84
KAD	121	139	131	137	135	126	131	129	122	113	105	103
LOS	98	97	98	91	82	95	103	107	112	90	82	88
MIU	130	139	139	147	150	130	141	116	126	114	117	119
PHC	98	109	93	91	108	97	101	108	109	89	84	89
SOK	134	139	139	142	143	126	132	129	119	117	108	114

4 Discussion

The optical loss results presented in the previous section are percentage reductions from a cleaned, low iron glass coupon. This section summarises and discusses the key findings based on critical observation and evaluation of results considering additional parameters such as weather, atmospheric particle, and AQI presented in the methods section.

The transmittance losses values obtained from the results shown in the previous section highlighted a significant variation between a cleaned coupon and coupons exposed to outdoor weather conditions. The most intriguing finding considering the optical transmittance results in high losses identified in coupons position on the horizontal plane across all the soiling stations. The greatest soiling among the annual coupon was recorded in ABV, the weather condition throughout the year as shown in Fig. 2 (a), where the dry season is longer than the wet season, and the AQI appears to be very high shown in Table 2 and Supplementary Fig. 17. However, it has been observed that the main pollutants are not extremely dangerous based on the information provided in Supplementary Fig. 18, but most of them have a very devastating effect on light transmittance based on the mineralogy analysis.

Climatic conditions such as humidity, wind speed/ direction, temperature and precipitation play a vital role in influencing soiling, but it could sometimes tranquillise the accumulation. Correlating findings of the optical losses in Fig 4 (a) - (d) with Fig. 2 (a) – (g) shows that weather parameters significantly influence accumulation. Considering monthly variation for North-Central (ABV), it was observed that the greatest optical losses were recorded from the January coupon, where soiling is assumed to be influenced by the increase in humidity and low precipitation, as shown in Fig. 2 (a). In the South-East region (ENU), the highest accumulation was recorded when the precipitation (rain) was lowest and wind and humidity were low, as presented in Fig. 2 (b). The greatest optical loss recorded in North-West (KAD and SOK) and North-East (MIU) occurred when precipitation was zero or low, the humidity was low, and wind speed was averagely high, as shown in Fig. 2 (c) and (g). Most significant accumulation transpired in South-West (LOS) and South-South (PHC) when precipitation was lowest, the wind was low, and humidity was high, as shown in Fig. 2 (d) and (f). Conversely, the lowest accumulation that translated to low optical losses was recorded when precipitation turned to be the highest across all the regions, as shown in Fig. 2 (a) – (g).

The seasonal optical transmittance losses results are additional information necessary to understand better the consequences of soiling on PV. The result shows wide variation between the dry and wet seasons, with the dry season showing the most significant losses in the Northern region due to Saharan dust (during Harmattan season) and while the wet season presents more losses in the Southern part. A most significant optical loss was recorded during the dry season in ABV, which is related to massive ongoing construction activities in the federal capital territory (including road, rail, and building construction) [35]. On the other hand, the most significant optical loss recorded during the wet season was in PHC, which is related to the region's massive oil exploration activities. The high optical losses rate in the South part of the country during the wet season is due to the longer duration of the wet season, which comes with light rain that lasts for about nine months, as shown in Fig. 2 (f), because of its proximity to the Atlantic Ocean. Fig. 2 (a) shows that the wind speed in ABV is the lowest. The humidity is highest considering the Northern region and similarly for PHC in the Southern region, highlighting why more accumulation was recorded in ABV during the dry season and PHC during the wet season. More detailed information on the seasonal variation in the region causing soiling is presented in Chanchangi et al. [2].

Considering the monthly timestamp as an exposure period, the Optical losses result provides vital information that breaks down the soiling formation data into a period that can be employed in many applications such as research, installation planning, and maintenance planning. The results illustrated different optical losses each month, and the greatest was recorded on the ABV coupon installed on a horizontal plane in February. Other months such as November, December, January, and April also presented significant losses. According to weather data provided in Fig. 2 (a), (b), (c), (d), (e), (f), and (g); all the above months tend to fall within the dry season with an influx of the Saharan desert that sweep the country. The atmospheric particles are blown away by the low-level jet (North-easterly)

winds from the far North (Northeast and Northwest) to the Northcentral and then the Southern part of the country, causing high formation on surfaces in the Northcentral since the wind speed tends to drop around the region. AQI tends to be very high during these dry months across the country, but the cumulative annual average would end up very low. The AQI and the main pollutant AQI might be very high in some regions, and the soiling level would be shallow; the high wind does not allow settlement on platforms.

The angular variation of optical losses might be assumed to be always in the same pattern, where the most significant losses should always be recorded on the horizontal plane, and the losses reduce as the angle changes towards the vertical plane. However, it has been reported by Gholami et al.[36] that dominating incoming wind could significantly influence the adhesion and accumulation of particles in various angles, resulting in a disparity to the above assumption and a variation in the optical losses result obtained from this study. The greatest optical loss is not continually expected to be obtained at the horizontal plane all the time and in the entire region since the dominant wind direction could play a significant role in the resuspension of deposited particles from a coupon. In addition, the optical losses in correlation with angular variation presented in this study provide data that could be used for loss correction of various angles when installations are to be made on angles other than the ones provided. It is also to accommodate other PV applications, as earlier presented.

SEM/EDX analysis assisted in validating the optical losses by highlighting minerals that can absorb, attenuate, or scatter light to penetrate them. Table 2 presents SEM/EDX results showing that some of the particles on ABV's coupon are translucent and opaque, which could reduce light penetration. A significant amount of dust accumulated on the coupon because the wet weather condition (light rain in February) created cementation and lower wind velocity. A mineral particle such as Montmorillonite was found on the coupon, opaque and came from clay, and is predominantly used as a building material in the region. Chamosite transparency is translucent to sub-translucent and is a mineral found in the environment with low iron deposition. Chanchangi et al. [11] reported that this mineral could be found in laterite and sometimes loamy soil, and these are also used as building materials in the region. Spodumene is obtained when minerals are ignited, and this could be due removal or breaking of rocks for road construction, quarry activity or mining. These minerals identified from the ABV coupon show that the region's high soiling rate is directly related to construction activity and weather activity. To further validate the minerals recorded, the main pollutant and AQI from Table 2 were analysed, which shows that PM_{10} and $PM_{2.5}$ are very high values; this supports the claim that particles recorded on the coupons are from construction sites, landfills, and windblown dust.

Findings show optical losses on all coupons, even though few are minor. However, accumulation causes required additional information, as included in some paragraphs above. The analysis shows that particles in the atmosphere or the AQI cannot be used as the only source for determining the accumulation rate as wind speed, humidity, and precipitation could play a vital role in allowing particles settlement on surfaces.

The soiling mapping result presented in the previous section highlighted a significant variation between the result from this study and information presented by the GSA, with higher soiling rates determined during this study. The variation observed from the annual mapping is significantly wide. The maximum variation was observed from ABV, where a 746.69 kWh/kWp difference was recorded between the PV output using soiling data from this study and the PV yield based on 4.5% soiling. All the annual soiling data from the other sites in this study presented higher soiling losses than the GSA constant value, shown in Fig. 5.

Each season presented a massive variation between the PV yield (with soiling data obtained from this study) and GSA PV yield (a constant soiling rate of 4.5%). The maps show that the most significant disparity recorded in the Northern region during the dry season was from ABV with about 536.14 kWh/kWp difference, while the most significant disparity recorded during the wet season was from PHC with about 388.12 kWh/kWp. This regional soiling disparity that is directly related to seasons is due to the intertropical displacement caused by the Coriolis force. During the dry season, the PV yield is higher in the Northern region, and the most significant soiling loss was recorded in the North-central. While during the wet season, the Southern part tends to have a high PV yield due to the more extended

duration of the season in the region and the most significant soiling loss was recorded in the South-south region. As earlier mentioned, the dust movement is influenced by north-easterly low-level jets wind from the Saharan desert during the dry season. During the wet season, the dust movement is influenced by south-westerly winds from the Gulf of Guineas and the Niger-Delta region, where oil exploration activities are ongoing. By observing the pattern of the weather information provided in Fig. 2 (a) to (g), it is easy to know that the Northern and the Southern region have a climatic pattern that substantially influences dust settlement and accumulation on an exposed surface. The maps in Fig. 6 and Fig. 7 illustrated higher PV yield degradation due to soiling rates in both seasons compared to GSA values, and these seasonal variation data can be found in Fig. 8.

It is necessary to understand the monthly PV yield, considering the effect of soiling. There are individual monthly differences between PV yield employing soiling data from this study and PV yield with a 4.5% constant soiling rate. A closer examination of results reveals that some months (mainly during the dry season), such as November, December, January, February, March and April, have a higher PV yield degradation rate variation. The most significant variation was observed in February, where about 31.05 kWh/kWp disparity was recorded in ABV, followed by December with 27.53 kWh/kWp in PHC, January with 24.81 kWh/kWp in LOS, November with 21.85 kWh/kWp in ABV. The few negative figures shown in Fig. 8 are when GSA soiling rates in percentage become higher than the optical losses recorded from this study. Variations are minor during the months that fall within the wet season. Some months have PV yield with soiling values that turns out to be lower than GSA values because the soiling loss is lower than 4.5% (GSA soiling loss). The map for the month of May illustrated that PV yield (with soiling determined from this study) in three regions (ENU, LOS, and PHC), all from the Southern part of the country are less than 4.5% (GSA soiling loss value); the June map shows only one region (KAD); the August map shows two areas (KAD and MIU); the September map shows three regions (ENU, KAD, and LOS); while the October map shows only one region (ENU). Variation data for each month is shown in Fig. 8.

As earlier stated, the PV yield presented in the Global solar atlas was clearly emphasised that it does not adequately account for a number of important factors that potentially impact the PV output. However, soiling data cannot be constant, and caution should be taken when generalising such information since it can significantly impact the PV yield and mislead the potential users of the information. The findings demonstrated more realistic and accurate soiling losses, as shown in Fig. 8, where the disparity values of the soiling site were illustrated, comparing PV yield with soiling data from this study and GSA PV yield with constant 4.5% soiling considering the exposure period.

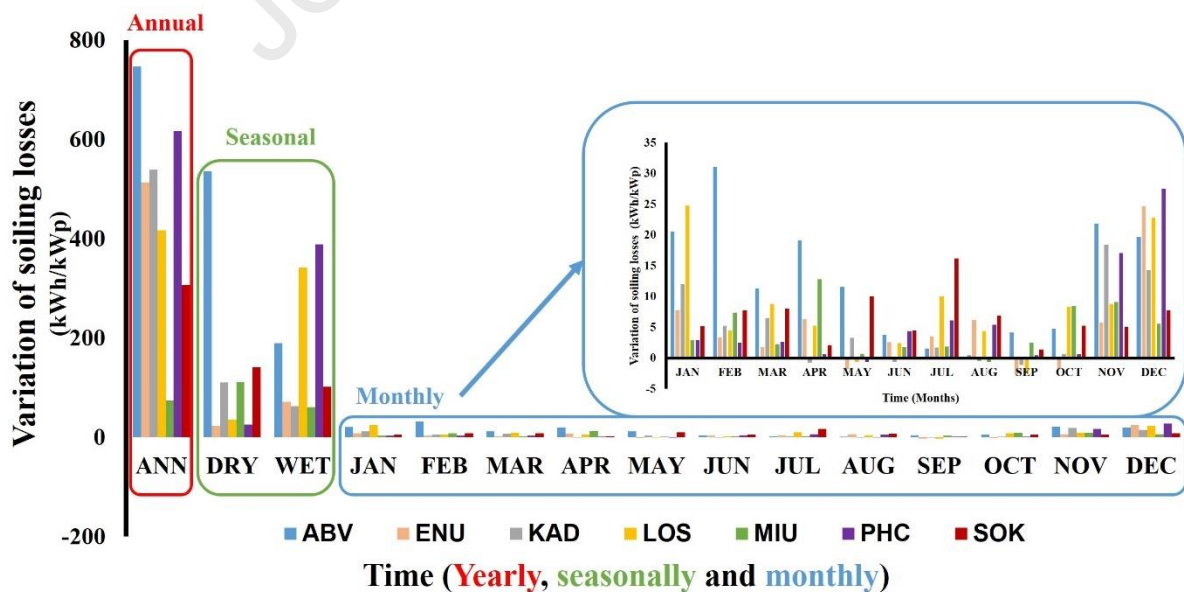


Fig. 8. Variation of soiling losses between GSA and results from this study. The ANN highlights the annual variation, Dry and Wet show the seasonal variation, highlighting dry seasonal variations and the

latter shows wet seasonal variations for the seven regions. The Monthly illustrates the variation of each region in every calendar month. Soiling stations are highlighted using various colours in the chart.

The low-cost novel approach employed in this study has potential advantages; it could guide research to know the appropriate mitigating techniques required for a particular region in the country and prompt a significant step toward finding a lasting solution to the PV soiling problem. The presented research concept could be replicated elsewhere, from regional to global scale. Furthermore, it could be used for other applications in the glass (to determine the period cleaning cycle for cleaning exposed glass to reduce cost); financial (to calculate more accurate funding to invest in developing large scale solar energy assets); chemical (provide information on the appropriate chemical material to use for developing self-cleaning coating); mechanical (to types of machinery that could be used for optimum maintenance design at lower cost); and mining industries (to highlight potential mineral deposition across the region of study). It is clear that there are significant benefits from the output of this study since the previous information is somehow misleading due to less accuracy of the soiling information, which might be causing wrong installation and maintenance planning that could lead to less yield or system failure at the extremity. The findings provided benefits such as more accurate and realistic information for better PV installation and maintenance planning to achieve more yield. The result could assist in optimising the maintenance procedure to generate more output at less maintenance cost.

5 Conclusion

Soiling has a detrimental effect on PV performance, and this problem is unacceptably underestimated and understudied in some regions, such as Nigeria, with massive solar energy potential, low PV penetration and high energy deficit. This study demonstrated high optical losses in a region with enormous solar energy potential but shallow PV penetration. The results show that coupons positioned on horizontal planes accumulate more dust than the tilt angle (45°) and vertical plane, providing a positive advantage of less soiling losses to integrated RE due to varying angular position. The work reveals ABV as the region with the most significant soiling loss in the country and February as the month when the most considerable soiling loss occurs. The outcome shows that the Northern region has a higher soiling loss during the dry season, with ABV having the most significant loss, while during the wet season, the Southern region shows a higher accumulation, with LOS and PHC being on top of the list. SEM/EDX analysis confirmed that minerals collected on coupon surfaces negatively affect light transmittance, causing the optical losses to be recorded. The AQI and pollutant data validate the type of particles recorded. The weather condition shows why high accumulation values are recorded from each region and during a specific season, impacting seasonality variation. The significant disparity has been illustrated when results from this study are correlated with already published work.

The study demonstrated a unique technique that investigated optical losses by employing a radical approach and showing a wide variation of soiling losses which has been under-reported by previous studies and also grossly underestimated, which might be due to overlooking regional variability and the seasonal difference that plays a vital role in increasing or decreasing the losses rate. In conclusion, this work offers a successful low-cost approach that could be employed to determine soiling induced losses on PV worldwide. However, the method could be further refined by increasing the number of soiling stations and narrowing the distance. It is recommended that a similar soiling station should be installed in some regions to acquire *in-situ* soiling data that would reduce the variation gap discovered in this study and provide researchers, policymakers, potential PV investors, and commercial PV companies with more realistic PV yield potential. Finally, the information presented in this study should use to determine the appropriate cleaning procedure and optimising it to improve the penetration and scale-up of the solar energy technologies in regions with high energy demand and low penetration to achieve the sustainable development target goal 7 [37] (*"Ensure access to affordable, reliable, sustainable and modern energy for all"*).

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Competing interests

The authors declare no competing interests.

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Supplementary Material.

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Competing interests

The authors declare no competing interests.