In-Situ Assessment of Photovoltaic Soiling Mitigation Techniques in Northern Nigeria

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Abstract
The photovoltaic (PV) system's performance suffers from intensifying external factors such as soiling, particularly in arid and semi-arid regions with massive solar energy potential. Mitigation techniques are one of the crucial factors to prevent and restore PV performance. Therefore, in this study, five cost-effective mitigation techniques such as natural cleaning, manual cleaning with squeegee/water, manual cleaning with a brush, self-cleaning with a hydrophobic coating, and mechanised cleaning with a wiper using acrylic plastic and low iron glass coupons were executed solar farm based in Nigeria. The finding shows that the self-cleaning technique provides high preventive and restorative performance during the wet season (August) with ~99% optical efficiency for a glass. Both manual cleanings with squeegee/water and self-cleaning demonstrated high optical efficiency, with first being the greatest with 96% and the latter 95 % during the dry season (January) on a glass coupon. Furthermore, results show that low iron glass is more durable than acrylic plastic when exposed to the harsh condition. Our study envisages the implemented PV soiling mitigation technique's performance and comparative cost analysis of a complete pledge PV panel over a longer duration in different regions, considering the factors influencing PV system performance.

Nomenclature

Dry	Dry season
Wet	Wet season
VDW	Van der Waal force
T (λ)	Spectral transmission
S(λ)	Relative spectral distribution of solar radiation
Δ	Change
Δλ	Change in wavelength
τ_x	Transmittance data of a coupon positioned at an angle relative to a horizontal surface
τ_{clean}	Transmittance data of a clean coupon
$\tau_{Unexposed}$	Transmittance data of a clean coupon
$\tau_{exposed}$	Transmittance data of a clean coupon
SL_{Coupon}	Soiling value of a coupon
PM_{10}	Particulate matter with diameter size ≥10 µm
$S_{(H\&S)}$	Safety (health and safety)
$R_{(I)}$	Reliability
$M_{(O+M)}$	Maintenance (operation and maintenance cost)
$E_{(D+Q)}$	Engineering design (Design and quality)
$O_{(O+P)}$	Operation (operational and success probability)
η	Efficiency
CDC	Solution C, Solution D, and Solution C
γ^{lv}	Liquid surface free energy

γ^{sv}	Coupon surface free energy
γ^{sl}	The interfacial free energy
θ	Contact angle
TTiP	Titanium (IV) isopropoxide
OH●	Hydroxide
O_2^-	Oxygen
DI	deionised water
SiO_2	Silicon oxide
TiO_2	Titanium dioxide
ZnO	Zinc oxide
ITO	Indium Tin Oxide
M-ZnO	The microspheres Zinc oxide
TBOT	Tetrabutyl Orthotitanate
TEOS	Tetraethyl-orthosilicate
HDMS	Hexamethyldisilazane
C_i	Initial cost
C_m	The estimated monthly cost of maintenance.
$\sum p_{(PPE)}$	The total price of all the PPEs required,
$p_{(tool)}$	The price of the tool.
$\sum p_{(mat)}$	The summation price of coating materials,
W^{flex}	Wages for re-coating
$\sum p(comp^1)$	The summation price of all components used in fabricating the mechanised platform.
$\sum p(com)$	The summation of all the components (example: wiper lade and battery) must be changed after one year of operation.
w	The wages for coating the hydrophobic layer on the coupons.
cyc	The number of cycles required in a month,
L	The labour
Q_{H_2O}	The quantity of required water.
l	Number of workers,
$p_{(PPE)}$	The price of *PPE*
t_2	the time coating is expected to degrade and requires re-coating (48 months)
$p_{(tool)}$	The price of a tool
$o_{(tool)}$	The number of tools
t_1	Time considering 12 months maintenance cycle.
p	Price

Abbreviation

EDS	Electrodynamic screen
Eq.	Equation
EU	European United
Fig.	Figure
NIR	Near Infra-Red

PPE	Personal protective equipment
PV	Photovoltaic
SEM	Scanning electronic microscope
STC	standard test conditions
UK	United Kingdom
USA	United State of America
UV	Ultraviolent
VIS	Visible

Unit

A	Ampere
cm	centimetre
°C	Degree centigrade
°	degree
E	East Direction
EUR	Euro (European currency)
eV	electronvolt
g	gram
hrs	Hours
km/h	kilometre per hour
m	metre
mm	millimetre
ml	millilitre
m/s	metre per second
MWh	Megawatt hour
MWp	Megawatt power
MW	Megawatt
nm	nanometre
N	North Direction
sec	Seconds
£	Pounds sterling (Great Britain currency)
V	Voltage
W	Watt

Keywords: PV Soiling, Mitigation Techniques, Optical Losses, Performance

1 Introduction

Recently, photovoltaic (PV) soiling has rapidly attracted significant interest across the globe, as it is a limiting factor that reduces technology's yielding performance. As a result, substantial research time and resources are tailored to improve system efficiency in standard test conditions (STC). However, less attention is provided to the viability of the existing system's performance and sustainability when exposed to harsh conditions in arid and semi-arid regions [1, 2] with great solar irradiance potential and a wide gap between energy supply and demands such as Nigeria. Furthermore, dust and impurities accumulation on PV system surfaces presents a significant problem to the output performance of the PV technology [3-5], causing substantial yield losses due to scattering and absorption of incident irradiance on PV cell [6-9].

Deb and Brahmbhatt [10] stated that airborne dust particles in the path of an incident radiance of a PV device and deposited impurities on PV covering surfaces act as barriers to the impending solar radiation in areas with massive solar energy potential such as arid and semi-arid regions. It decreases the light transmittance, leading to power losses [11]. Its rate widely varies with location, surface covering material and seasonal variation [10, 12, 13]. A wide range of variation of the effect of dust accumulation on PV was reported in the literature, ranging from 0.51% in the USA [14] to about 98% in an indoor study [5]. However, no study has provided a permanent cleaning rate to mitigate PV soiling [4]. The use of conventional cleaning approaches tends to have a significant financial implication [15]. Bunyan et al. [16] stated that studying an environment's weather condition is a prerequisite for developing a large solar project. It can prevent performance losses by determining the cleaning cycle's optimum frequency. However, widely employed PV covering material based on plastic and glass is ineffective to avert dust accumulation on its own [2, 17]. Shaik et al. [18] reported acrylic plastic and low iron glass as the widely employed PV surface covering materials; however, the materials on their own are ineffective in terms of averting dust accumulation [2, 17]. Therefore, Acrylic plastic was included in the experiment since it has high transmittance (92%) and a low refractive index. In addition, it is commercially applied for build-in PV and is used for CPV [19]. Gupta et al. [4] highlighted the research gap investigating PV surface covering material and the economic feasibility of various approaches.

Mitigating the problem of dust accumulation on PV covering surfaces is vital for the penetration and sustenance of renewable energy in the developing world. Therefore, the scientist has put a massive effort to develop a mechanism that can prevent soiling losses or restore optimum PV output performance, and several techniques were reported by Chanchangi et al. [13], Gupta et al. [4], and Jamil et al. [20]. Each technique presents a different level of performance concerning the environmental condition of the location it has been deployed and the type of PV cover surface it is cleaning. However, some techniques have a long list of drawbacks, such as cost and uncontrolled water requirement supply, known as the primary concerns for the region in focus [21, 22]. This report presents a brief highlight of the main soiling mitigation approaches in the subsequent paragraph.

The natural cleaning technique is a restorative approach of cleaning where rainfall, wind and gravity are expected to remove accumulated particles from the PV surface and restore their potential performance [8, 23]. It is the low-cost approach and sometimes tends to be significantly effective [2], while sometimes it could cause more damage by influencing more accumulation [24].

The Manual cleaning with squeegee and water technique is another integral approach that is highly labour intensive. It requires personnel to employ small tool squeegee, wipes or towels to remove accumulated particles on PV surface through simultaneous scrubbing and washing, including water addition [10, 20]. In addition, detergents and other cleaning chemicals are sometimes employed to enhance cleanliness. This approach is amongst the effective and reliable cleaning method that could restore PV performance [25]. However, it has been reported to have the potential of causing an abrasion on PV covering material and is relatively expensive in the developed country due to labour involved [10].

The Manual cleaning technique with a brush is another integral approach that is highly labour intensive. It requires personnel to employ small tools such as brushes to remove accumulated particles on PV surface through simultaneous scrubbing and brushing [10, 20]. It is relatively expensive in the developed country due to the labour involved and has been reported to be causing severe abrasion on PV surface covering material [10]. As a result, the effectiveness of this approach is considerably low in some regions [25].

A mechanised cleaning approach is a restorative method that employs automation technique through robots cleaning, blowing by vortex generators, vibration, and mechanical wiping [2, 8]. For example, Williams et al. [26] reported that 95% of PV output could be restored through ultrasound vibration, removing accumulated dust on PV surfaces. However, a decade later, Deb and Brahmbhatt [10] and Jamil et al. [20] stated uncertainty on the efficiency and thoroughness of cleaning capacity of all mechanised cleaning and its high initial and maintenance cost.

Automated/robotic cleaning is an effective restorative technique that could clean the entire PV surface and be operated manually or automatically with accuracy and flexibility. This technique is sometimes categorised under a mechanised approach. It is configured according to requirement and comes with sensors, controllers and wiper or brushes. The system is designed to act with fast response, high stability, and operate independently (unmanned), low power consumption, and reduced labour cost [20]. Although it reduces the labour in the cleaning module, it has a very high initial cost and requires periodic cleaning. It could also cause abrasion and can be unreliable in some cases [10]. Recently, this approach is widely adopted and undergoing intensive research at different institution globally [27]. Azouzoute et al. [28] reported a robotic cleaning device developed by SOL Bright Technology to eliminate about 99% of accumulated dust and improve the 7-15% performance output of a large solar farm. However, this comes at a high cost and required monitoring.

The self-cleaning technique is a preventive and restorative passive approach that resist dust accumulation on PV surfaces through repelling achieved by PV surface modification, coating (hydrophobic or hydrophilic layer), and electrodynamic screen (EDS). The EDS removes using electrostatic forces to repel dust particles when an electric field is established on surfaces of the covering material [21]. It is reported to restore 90% of PV output performance by removing 80% of accumulated dust [29]. However, Guo et al. [30] examine the technology's performance in outdoor condition and reported efficiency degradation from 40% to 14% over four days. Nundy et al. [31] investigated hydrophilicity using Zinc oxide (ZnO) and achieved a 2.8° (super hydrophilicity) wet contact angle depositing the microspheres (M-ZnO) on an Indium Tin Oxide (ITO) glass substrate. The compound's morphology shows an average 41.5 nm crystallite size with a bandgap value calculated from the ultraviolent to visible (UV-VIS) absorption spectrum found to be 3.1 eV. Hydrophobicity uses the lotus effect to prevent or remove dust from PV surfaces using a nano-structured layer [32]. The coating resists the adhesion of dust particles to the PV surface but requires water to eliminate it. However, this technique is expensive on a large scale [20], and its optimum efficiency only lasts between 3-4 years [33] and two years, according to Gholami et al. [34]. As mentioned above, the techniques have the individual capacity to reduce dust. Still, no flawless approach has been recommended for the region in focus.

Renewable energy sees rapid investment coming its way in developing and developed countries due to climate change and energy security [2]. Nigeria has recently commissioned a third solar farm (3.5 MWp of solar PV, 8.1 MWh energy storage system and 2.4 MW of backup generators) and the largest off-grid in sub-Saharan Africa [35] in huge investment towards developing its renewable energy sector in the arid northern region of the country. However, in a recently completed study, it has been observed that soiling could cause an output loss of about 68% to 78% when the installation is left unclean for 12 months in the same city that homes two large operational solar farms. Chesnutt et al. ([17] stated a need to prevent energy losses by providing a cost-effective soiling mitigation technique relatively neglected. Piliougine et al. [11] recommended evaluating PV cleaning cost and the economic impact of output losses caused by soiling for large PV plant. However, the economic impact has been provided in the literature [36-38]. Ilse et al. [36] and Ghosh [39] stated, in 2018, the electricity generation from PV was reduced by 3% - 4%, resulting in revenue losses of around €3 - €5 billion, and this is related to soiling losses which is further projected to reach €4 - €7 billion by 2023. Therefore, this study comparatively investigated the performance of various mitigation techniques on two PV surface covering material (acrylic plastic and low iron glass), considering seasonal variations in the arid region of Northern Nigeria. Thus, neither cost analysis nor economic implication was presented. However, the approach used in this study could provide guidance to be adopted and applied in other regions since cost analysis varies with location (based on the economic capacity), as later described in the methodology. Five methods were investigated using coupons during the dry season and the wet season to determine the suitable and effective approach in various seasons and identify the appropriate PV surface covering material for the region.

Despite the extensive work and progress made in resolving soiling problem using both restorative and preventive approaches provided in the literature, significant studies are limited to examining a single technique, and others focused on reviewing publications reported from different regions. There is an insufficient investigation, comparative analysis and extensive performance studies of the techniques under the outdoor condition in the same site, considering variables (seasonal variation, PV surface covering material, and weather parameters) used in this study. The solution might probably lie in considering more variables, as each technique has advantages/disadvantages and their effectiveness are dependent on the variable mentioned above. To determine an appropriate one for a region, there is a need for a comparative performance study of the various techniques, which is relatively neglected. This study has two-fold contribution: first, developing and examining different PV soiling mitigation approaches in the outdoor condition in a region with massive investment in solar PV. Secondly, investigating the system performance using a multivariable method. The finding could prevent future unnecessary PV output losses due to soiling in the region. This study demonstrated a relatively low-cost approach based on findings reported in the literature [2, 10, 20, and 36] to investigate the most suitable techniques for a region and stimulate more research across the PV soiling community and scientists. This study could serve as a foundation to estimate the possible frequency and financial commitment for PV farm maintenance in the region that could entice prospective investors and governments.

2 Method

The research examines five low-cost PV soiling mitigation techniques to solve a persisting soiling problem that adversely affects PV performance. Bayero University Kano 1 MW solar farm (11°59'02.1"N, 8°28'52.5"E) is where coupons were exposed to examine dust level accumulation. It was carefully selected since it is the most polluted country [40] with an operational solar farm. A total of ten low iron glass coupons and ten acrylic plastic were employed in this experiment, where each coupon had a dimension of 50 mm x 50 mm x 4 mm. The typical transmittance for low iron glass is 91% and 92% for acrylic plastic at UV/VIS range [41, 42]. However, when an anti-reflective coating is applied, it improves the transmitivity [41]. Therefore, clear coupons were employed rather than coupons with anti-reflective coating since the self-cleaning coating with Tetraethyl-orthosilicate (TEOS) as precursor also provides anti-reflective around the visible range of wavelength. Moreover, it is also essential to highlight the transmitivity range of the actual coupons without coating. At first, ten coupons, including five low iron glasses and five acrylic plastics, were exposed for thirty-one days during the dry season (January 2020). Then, another set of 10 coupons were exposed for the same duration during the wet season (August 2020). This exposure variation is to examine the performance considering the climatic condition of the region. Finally, coupons were exposed on the various platforms according to their cleaning methods. Chanchangi et al. [13] reported that soiling processes around the study region occur in two patterns; the first is during the dry season, where accumulation is related to dry Harmattan dust and some dry dust with light rain/dew on surfaces. The latter is during the wet season when windblown dust meets with water droplets/dew that accumulated on the PV surface covering material. This knowledge of weather activity in the region obtained in the literature helped determine incoming wind direction during the two-season for coupon's surface orientation during exposures and the months with peak [13]. It was reported by Kazem and Chaichan [43] that incoming wind has a more significant influence in removing particles from the surface.

2.1 Cleaning techniques

2.1.1 Hydrophobic self-cleaning coating

Hydrophobic coatings have low mechanical stability due to their high surface roughness. Silicon oxide-titanium dioxide (SiO_2-TiO_2) composite layer can help retain the coating's stability for several cycles. Rosales and Esquivel [44] reported that TiO_2 offers photocatalytic property, chemical stability, low toxicity, highly available and optical properties since it possesses high scattering, resulting from a high refractive index and large bandgap. While, SiO_2 exhibit thermal stability, hydrophobic and hydrophilicity properties [44]. Composite SiO_2-TiO_2 has been reported to enhance hydrophobicity when deposited on marble [45], improves the contact angle, anti-reflection and lower 1.4 nm roughness of glass [46]. Wu et al. [47] examined the properties of composite SiO_2-TiO_2 and reported that SiO_2 support hydrophilicity and stability of nanoporous TiO_2. The presence of TiO_2 in composite decrease the contact angle [44], but Ye et al. [48] reported a design with a triple layer of SiO_2, TiO_2 and SiO_2–TiO_2 using tetrabutyl orthotitanate (TBOT) and Tetraethyl-orthosilicate (TEOS) as precursors and Hexamethyldisilazane (HDMS) for anti-reflective surface modification. Their approach increases average transmittance in the visible region and improves the contact angle, proving that hydrophobicity can be improved by employing HDMS. This study adopted Ye et al. [48] approach in developing a self-cleaning to sustain the coating's transmittance and stability.

The hydrophobic coating development was carried out using a solution-processed silica-titania composite. The overall fabrication is schematically represented in Fig. 1. The details of the fabrication protocol have been described as follows. It was prepared using the following procedure:

Solution A was prepared using 2.1 ml of Tetraethyl-orthosilicate (TEOS) deposited in a beaker and mixed with 30 ml of ethanol. This solution was stirred for about 30 minutes at room temperature. After that, 2.0 ml of Hexamethyldisilazane (HMDS) was added and further stirred for 15 minutes at room temperature. Then 3 ml of deionised water (DI) was added to the solution and was stirred for an additional 3 hours to make it a transparent solution.

Another solution (Solution B) was prepared using A 5 g of SiO_2 (Silicon dioxide) nanoparticles mixed with 25 ml of butyl acetate. The solution was stirred for 4 hours at room temperature.

Solution A and solution B were mixed in a beaker at a 1:1 ratio to form solution C, and it was stirred for an hour at room temperature. Afterwards, solution C was kept ageing for ten days.

On the fifth day, solution D was prepared by mixing 0.12 (M) of TTiP [Titanium (IV) isopropoxide] in 100 ml of 2-propanol and DI water (1:1) mixture. It was stirred for twenty minutes at room temperature. Coupons (low iron glass and acrylic plastic) were dipped in solution C1 for five minutes and allowed to dry, dip into solution D for five minutes and allowed to dry, and dip again in solution C for five minutes and allowed to dry. These dipping procedures were repeated three times before the coupons are placed on a hot plate at 200°C for thirty minutes. Next, solution C1 was drop cast on another set of coupons employed about 7 ml of the solution on one side of the coupons using a similar pattern as used when dipping. Next, dropping solution C on coupons and allowed to dry, then solution D allowed to dry and finally, dropping solution C and allowed to dry. On the tenth day, another solution, D was prepared using the same quantity and materials mentioned above. Solution C and solution D were deposited using the dropping and dipping techniques on various coupons (low iron glass and acrylic plastic).

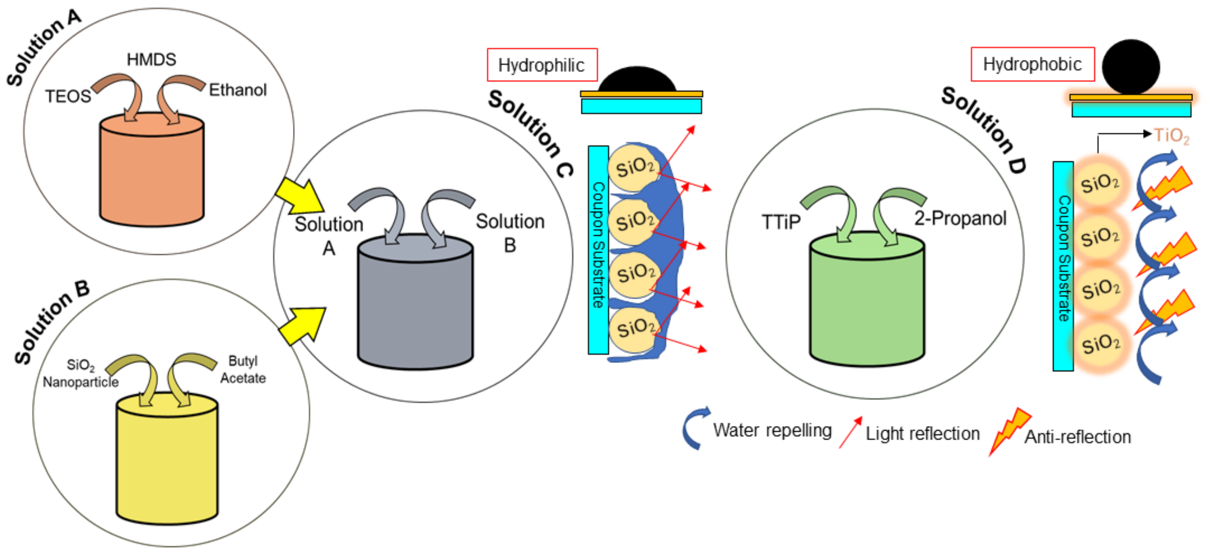


Fig. 1: Schematic representation of SiO_2-TiO_2 composite for self-cleaning coating development.

The intention of doing the solution C-solution D and again solution C repeatedly is to secure the film's homogeneity. Besides, only SiO_2 coating is not enough to protect water, and also sometimes it cannot show an anti-reflective property, and resulting dust accumulation can easily be there [44]. Moreover, the use of SiO_2 nanoparticles in powder form decreased the glasses' transparency. On the other hand,

TiO_2 exhibits anti-reflection property (reflected light at air/coating and coating/substrate interfaces), adequate transparency, and more light to the layer. Besides, the potent oxidising agents (O_2^- and OH●) on the coating surface generated by the charge carriers of TiO_2 during the absorption of high-energy photos can decompose absorbed organic molecules. SiO_2 further acts as inert support of the TiO_2 layer and accelerates the self-cleaning properties for the water and dust, and prevents oily dirt or organic matter. Hybrid SiO_2-amorphous TiO_2 also exhibited excellent stability under UV-light irradiation. Furthermore, SiO_2 imparts an efficient UV scattering because of the extensive refractive index of SiO_2 [15, 49, 50].

Dipping inside the TTiP solution forms an amorphous layer of TiO_2. It is essential to form such an amorphous layer, as amorphous TiO_2 contains a higher bandgap (~310 nm) than crystalline TiO_2 (~400 nm) [51]; therefore, it is a promising candidate to performance the UV-shielding ability. Thus, the sequential composition of SiO_2-TiO_2 is essential to improve the coupon substrate's mitigation property. Furthermore, these systems are easy to produce on a large scale at a low cost and exhibit high mechanical and chemical durability. Thus, these materials are suitable for bi-functional anti-reflective and self-cleaning coatings for large substrates for the solar module.

2.1.1.1 Coating surface wettability study

Wetting refers to the study of how a liquid deposited on a solid (or liquid) substrate spreads out or the ability of liquids to form boundary surfaces with solid states. The wetting, as mentioned before, is determined by measuring the contact angle, which is the liquid forms in contact with the solids or liquids. The wetting tendency is more significant the smaller the contact angle or the surface tension. It is expected that hydrophobic surfaces are partially non-wetting and regarded as having contact angles between 90° and 180°, while hydrophilic surfaces are partially wetting with contact angles between 0° and 90° (Fig. 2). The most commonly used method is the goniometer-telescope measurement of sessile-drop contact angles. Commercial contact angle goniometers utilize a microscope objective to view the angle directly. A drop is deposited on a surface in the static form, and the contact angle can be measured by looking at the descent through a goniometer (an instrument that measures contact angles). Ossila contact angle goniometer was employed to measure each coupon's average water contact angle value, which defines the coating's hydrophobicity. Eq. (2), known as Young's equation provided by Kung et al. [52] and Good [53], was employed to validate the coating's hydrophobicity. Uncoated coupons (low iron glass and acrylic plastic) were initially measured, and then subsequently, coated coupons were examined. Coated coupons were also subjected to optical transmittance checks to select the best coupon with a high hydrophobic rate and a high transmittance level.

$$\gamma^{sl} = \gamma^{sv} + \gamma^{lv} \cos\theta \tag{2}$$

where θ is the contact angle between the liquid and the coupon surface, γ^{sl} is the interfacial free energy of the solid or liquid, γ^{sv} is the coupon surface free energy, and γ^{lv} represents the liquid surface free energy. Eq. (2) is further illustrated in Fig. 2 for a better understanding.

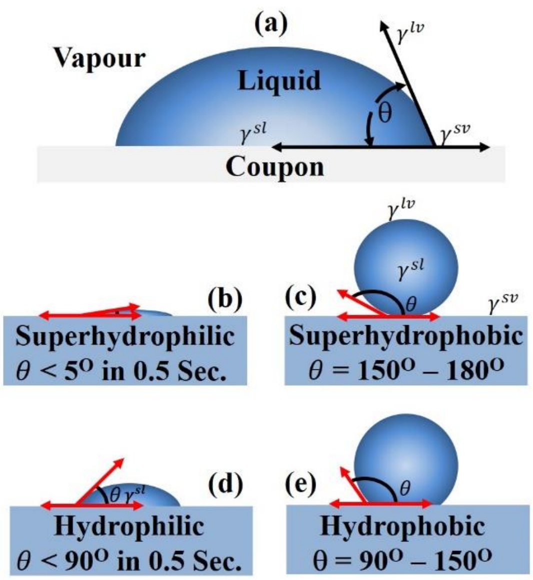
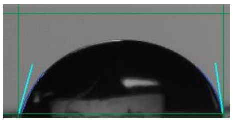
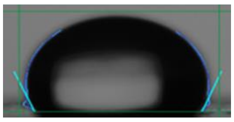
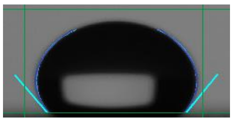


Fig. 2: Illustrative variation of hydrophobicity and hydrophilicity levels.

Findings illustrating a contact angle variation of a coated and bare coupon is provided in Table 1. It is compared with Fig. 2 to determine the status of various coupons.

Table 1: Captured images of hydrophobicity levels with their various levels of contact angles.

Coating Sample	Average Water Contact Angle	Captured Image
Bare Glass	35°	
Bare Plastic	77.5°	
Coated Plastic CDC-10-Dipping	110°	
Coated Glass CDC-10-Dropping	126°	

2.1.2 Mechanised cleaning

An in-house, low-cost mechanised cleaning platform was developed to examine how effectively mechanised cleaning performs in dry, dusty regions. The platform was developed using acrylic plastic with a 12 V Bosch motor wiper and its blade powered by a 12 V 4.5 Ah battery and a 15 A toggle switch non-illuminating. The battery is removable as alligators insulated clips were used to connect to terminals. The platform was designed using SolidWorks, and the file was exported as DFX to Boxford BGL 690 80 W Laser Cutter machine, where all the parts were cut into shapes. It was designed to allow placement of coupons at a 12° tilt angle, reported at the site's optimum tilt angle as earlier mentioned. The top platform has four slots to accommodate 50 mm x 50 mm coupons with 4 mm thickness (two low iron glass coupons and two acrylic plastic coupons). No abrasion will occur at the intersection point during the blade's movement. Fig. 3 illustrates the schematic diagram of the design with two digital images. Like other techniques, this cleaning approach was operated on once a week. The design could be improved using a sensor and an Arduino for automation.

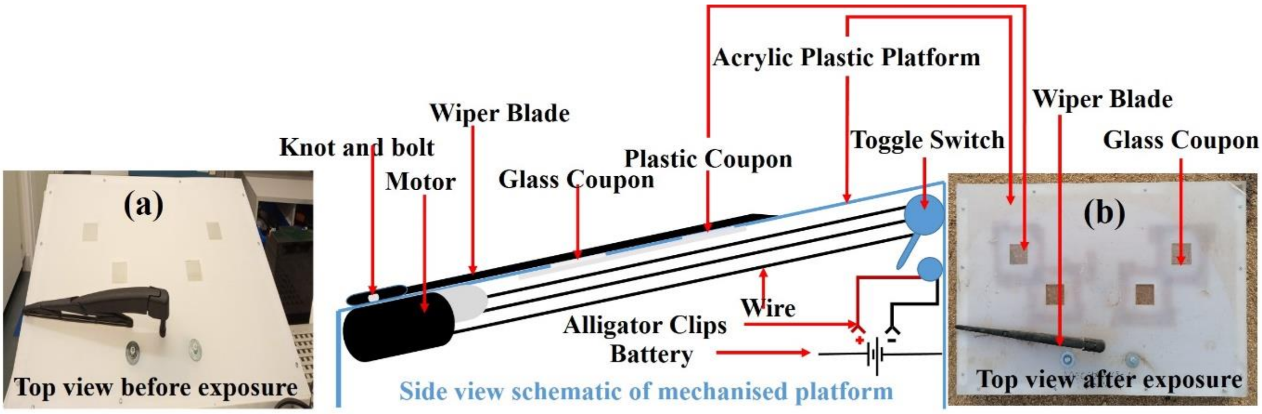


Fig. 3: Schematic diagram illustrating various mechanised cleaning platform components with two digital images (a) before and (b) after exposure.

2.1.3 Manual cleaning

The manual cleaning was divided into two categories: water and without water. Manual cleaning with water was conducted by pouring water on the exposed coupon's surface and employing squeegee to wipe off the surface. This procedure is performed once a week. On the other hand, manual cleaning with a brush, the cleaning technique used in the solar farm, was conducted using a dry brush to scrub the exposed coupons' surfaces. Again, similar to other techniques, cleaning is performed once a week.

Coupons that undergo manual cleaning, no cleaning and self-cleaning were exposed using an in-house developed platform that positioned coupons at an optimum tilt angle of the site (12°). Fig. 4 shows a digital image illustrating coupons exposure.

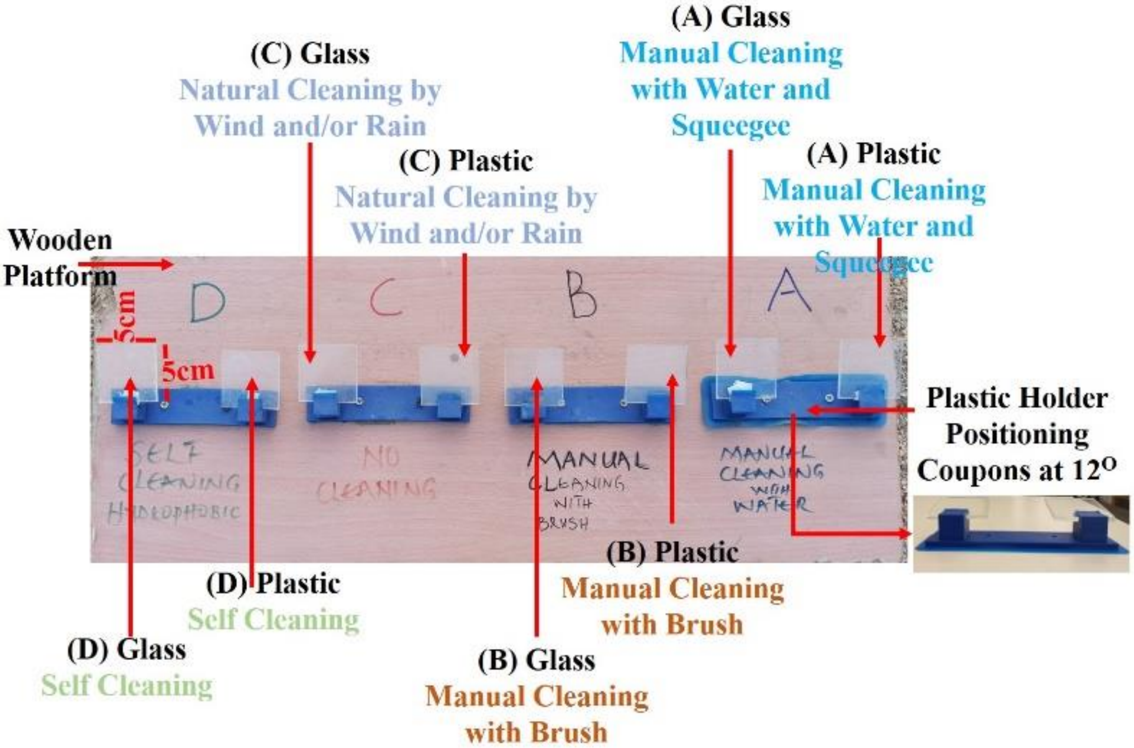


Fig. 4: Digital image of coupons placed on various holders.

2.2 Optical losses characterisation

All coupons were subjected to optical transmittance characterisation to determine the level of deterioration. Coupons are examined using a clean coupon (glass or plastic) as a baseline except for the self-cleaning, which were examined using the transparency of a coated before exposure as a benchmark to determine optical losses. The Perkin Elmer Lambda 1050 UV/VIS/NIR spectrophotometer was employed to conduct spectral transmittance measurement from UV (Ultra Violet), VIS (Visible) and NIR (Near Infra-Red) wavelength level. To determine which deposition technique provides the highest transmittance and establish a reference point for comparison, and Eq. (1) provided by Ghosh et al. [54] was used for validation.

$$\tau = \frac{\sum_{\lambda=250nm}^{1250nm} S(\lambda)\tau(\lambda)\Delta\lambda}{\sum_{\lambda=250nm}^{1250nm} S(\lambda)\Delta\lambda} \tag{1}$$

where τ (λ) is the spectral transmission, $\Delta\lambda$ is the change in wavelength and S(λ) is the relative spectral distribution of solar radiation.

Eq. (2) was used to determine the percentage difference between a soiled coupon and a clean coupon for manual cleaning technique, mechanised technique, and no cleaning. Still, for self-cleaning, the transmittance level was measured after coating was used as the baseline.

$$\text{Relative transmittance change } (\Delta\tau_x) = \frac{(\tau_{Unexposed} - \tau_x)}{\tau_{Unexposed}}(100) \tag{2}$$

where Δ is the relative change, τ_x is transmittance data of a coupon positioned at an angle relative to a horizontal surface, $\tau_{Unexposed}$ represents the transmittance data of a clean coupon or a coated coupon before exposure. It should be noted that relative optical losses values obtained using Eq. (2) were employed to determine the efficiency and soiling losses of the various technique since soiling loss could be calculated relative to the cleanliness of a PV covering material [55]. Therefore, Eq. (3) was directly employed as the soiling losses as PV modules were not deployed for the study.

$$SL_{Coupon} = \frac{\tau_{Unexposed\ coupon} - \tau_{exposed\ coupon}}{\tau_{Unexposed\ coupon}} \tag{3}$$

where SL_{Coupon} is the soiling value of a coupon, $\tau_{exposed}$ is transmittance data of an exposed coupon, $\tau_{Unexposed}$ represents the transmittance data of a clean coupon or a coated coupon before exposure.

2.3 Weather condition

The climatic condition of the site of study varies from dry that starts around October and last till April, and the wet season begins around May and lasts till September [56]. This study considers the climatic variation and exposed coupon on each of the two distinct seasons. Weather data such as wind speed and rain was collected to see the possible effect of natural cleaning from both. A Maplin professional weather station was installed on-site to capture the weather during coupons' exposure. Fig. 5 (a) and (b) provides wind velocity and rain rate. It is worth mentioning that coupons were exposed during the peak of both seasons, where high wind velocity is expected in both seasons. In addition, an increased rainfall rate is expected during the wet season, which significantly influences the high performance of the natural cleaning technique used as a benchmark for all others.

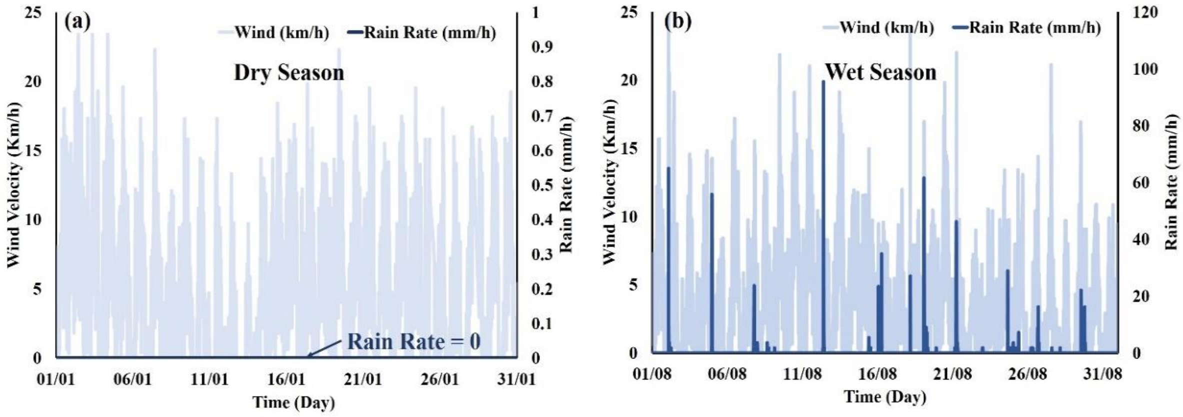


Fig. 5: weather charts illustrating wind velocity and rainfall rate during the dry season (a) and wet season (b), which are the two climatic condition of the study's site.

2.4 Technique's performance assessment

The performances of the soiling mitigation techniques were evaluated using five parameters: Initial cost, which is determined from the cost of the required materials for fabrication and hour of labour; a monthly operational cost which is determined from calculated, the ongoing cost of operation such as monthly wages for the operator, parts for maintenance over a particular duration, and contingency plan for parts failure; effectiveness of the technique which is determined from optical losses on both coupons; reliability which is determined from five factors (operation, engineering and automation, maintenance, reliable, safety); and limitation which determine from disadvantages reported in Jamil et al. [20]; Deb and Brahmbhatt [10]; Gupta et al. [4]; and observation from this study as shown in Table 2, Table 3, Table 4, Table 5, and Table 6.

A summation variable for each factor determined the value of a parameter presented in the result section. For example, hours of labour are determined using UK minimum wage (£8.72/hours) [56], and cost of labour is calculated using Nigeria minimum wage (£0.3125/hours) [57] since the maintenance operation is conducted in Nigeria. The UK minimum wage was used to calculate labour time during design and development since both the hydrophobic coating and mechanised platform were fabricated in the UK and transported to Nigeria. In contrast, the Nigerian minimum wage was used to calculate the continuous labour cost and equipment maintenance over time, considering the equipment's lifecycle time in question since human labour will be locals at the installation site.

The initial cost for mechanised and self-cleaning approaches was determined by summing the materials cost and the labour cost for fabrication considering estimated hours spent. Thus, the initial cost for manual cleaning is related to cleaning materials and PPE, and the zero initial cost was allocated to natural cleaning. Using Eq. (5), mathematical modelling was employed to calculate the initial cost of materials and wages for the techniques by substituting the appropriate value for each variable where applicable; otherwise, 0 is used for unrelated parameters accordingly.

$$C_i = \sum p_{(PPE)} + \ p_{(tool)} + \sum p_{(mat)} + W^{flex} + \ \sum p(comp^1) + w\ (\%) \tag{4}$$

where $\sum p_{(PPE)}$ is the total price of all the PPEs required, $p_{(tools)}$ represents the price of tools, $\sum p_{(mat)}$ signifies the summation price of coating materials, $\sum p(comp^1)$ denotes the summation price of all components used in fabricating the mechanised platform, w is the wages for coating the hydrophobic layer on the coupons.

The monthly cost was determined relative to each approach as follows: the Natural cleaning have zero monthly maintenance cost; the manual cleaning with squeegee and water comes with the monthly cost of water, the monthly cost of labour, the monthly cost of buying safety PPE (personal protective equipment) (cost are divided into months to spread the cost changing the PPE on an annual basis); the monthly cost for manual cleaning with a brush was determined by calculating the labour cost, tools and PPE; the self-cleaning monthly cost was calculated by splitting the initial cost of coating substances and fabrication labour/re-installing the covering materials into months since the coating is expected to be ineffective after four years as presented in the literature: the mechanised platform requires replacement of the battery, the cost of labour for maintenance operation. Mathematical modelling using Eq. (5) was employed to calculate the monthly cost implication of sustaining the performance of each technique by substituting the appropriate value for each variable where applicable; otherwise, 0 is used for unrelated parameter.

$$C_m = cyc_{(L_{(w\times l)}+Q_{H_2O})} + \left(\frac{p_{(PPE)}}{t_1}\right) + \left(\frac{p_{(tool)} \times o_{(tool)}}{t_1}\right) + \left(\frac{\sum p_{(mat)}+W^{flex}}{t_2}\right) + \left(\frac{\sum p(com)}{t_1}\right)(\%) \tag{5}$$

where cyc is the number of cycles required in a month, L is the labour which is derived from w workers' wages multiply by l number of workers, Q_{H_2O} is the quantity of water, p represents price, $p_{(PPE)}$ is the price of PPE, t_1 is time (signifying 12 months maintenance cycle), $o_{(tools)}$ is the number of tools, $\sum p_{(mat)}$ represents the cost of hydrophobic coating materials, W^{flex} is the wages for re-coating, t_2 is the time coating is expected to degrade and requires re-coating, and $\sum p(com)$ is the summation of prices of all the components (example: wiper lade and battery) required to be changed after one year of operation.

The change of transmittance reduction in percentage reduction for each coupon is used as the effectiveness value, which is determined by comparing a clean coupon and soiled coupon after exposure for all coupons except for coupons with a hydrophobic coating. Its effectiveness is determined by calculating the change in transmittance reduction in the coated coupon percentage before and after exposure. This used the value obtained from Eq. (6) below.

$$\text{Effectiveness } (\eta) = 100 - \frac{(\tau_{Unexposed\ coupon} - \tau_{exposed\ coupon})}{\tau_{Unexposed\ coupon}} \times 100 \tag{6}$$

The five reliability factors were allocated percentage for each variable and were summed up to determine how the system's reliability can operate. In this study, reliability is considered the likelihood of a product's safe and required performance over the stipulated time in a specific environment. A reliability model was adopted from Signoret and Leroy (2021), where they presented five reliability components (probability of success, durability, dependability, quality over time, availability to perform a function). These components were modified and into five components stated in Eq. (7), where each component is graded with 20%, and the summation was added to determine the system's reliability.

$$R_{Si}(\%) = O_{(O+P)} + E_{(D+Q)} + M_{(O+M)} + R_{(I)} + S_{(H+S)} \tag{7}$$

where operation ($O_{(O+P)}$) represent the availability to perform a function the success probability is high, engineering design ($E_{(D+Q)}$) standing for system design and quality of the system over its stipulated operational time, maintenance ($M_{(O\&M)}$) signifies the durability of the system in adverse conditions, reliability ($R_{(I)}$) denotes the dependability of the system to work alone, safety ($S_{(H\&S)}$) is representing health and safety, how safe the system could be operated. Values are allocated to each component considering the reported literature in relation to the process conducted in developing the approach.

Limitation constraint presented in the literature and observed during this study is allocated a percentage rating (20% each for a limitation) and was summed up. The difference from 100% was used as a percentage level. This is a rough estimate to illustrate the limitation and show how each approach has more than one.

3 Results

This section illustrates the findings where results are categorised into sub-sections: the optical losses section and the soiling mitigation technique's performance assessment. Both are further subdivided into their specific technique.

3.1 Optical losses and quantitative performance assessment

3.1.1 Manual cleaning with squeegee and water

The period of exposure plays a significant role in determining the optical losses. Despite the effort of weekly manual cleaning using water and squeegee, substantial optical losses were recorded of about 9% transmittance reduction on the exposed acrylic plastic during the dry season and 6% during the wet season. On the other hand, minor optical losses were recorded on low iron glass coupons with about a 4% reduction during the dry season and 3% during the wet season. Thus, optical losses on the low iron glass during exposure times are less than 50% compared to acrylic plastic. Fig. 6 illustrates both coupons' optical losses during the different exposure periods.

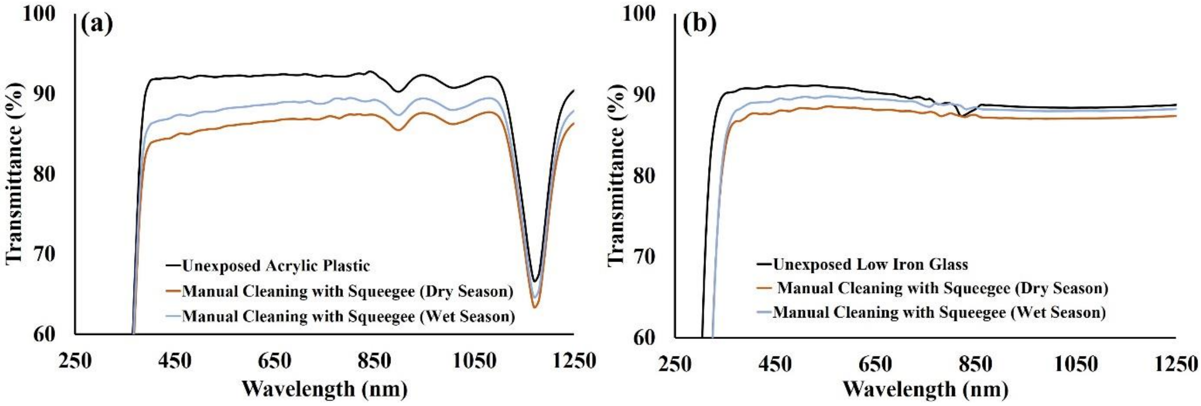


Fig. 6: Optical transmission losses variation of a soiled coupon with a clean one exposed under manual cleaning with squeegee/water (a) acrylic plastic (b) low iron glass coupon.

Performance evaluation was conducted using a multivariable approach. The finding for manual cleaning with a squeegee and water, as shown in Fig. 7, illustrated that the technique has a low initial cost for equipment required to accomplish the task; the reliability of this technique is average. The monthly maintenance cost is the minimum wage average in developing nations and developed countries such as the UK, USA, and EU. It is highly effective on both coupons but could sometimes cause abrasion. The method is rated high in limitation due to the tendency of causing electrocution since water is involved. Based on the findings presented in Fig. 7, this mitigation approach is rated as an average technique.

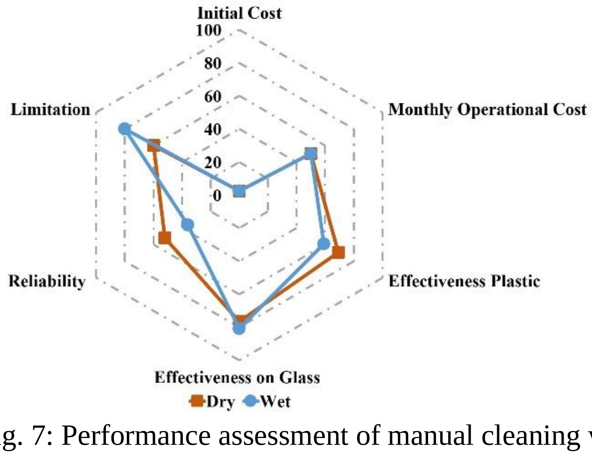


Fig. 7: Performance assessment of manual cleaning with squeegee/water illustrating cost variation, limitation, effectiveness on coupon cleaning, and reliability.

3.1.2 Manual cleaning with a brush

Higher optical losses were recorded when coupons, despite weekly manual cleaning using a brush with a considerable seasonal variation. The result demonstrates the common phenomenon where a significant loss of 17% was recorded on the acrylic plastic during the dry season and 14% during the wet season, as illustrated in Fig. 8. On the other hand, considerably lower optical losses were recorded from the low iron glass with about a 5% reduction in coupons exposed during dry and wet seasons.

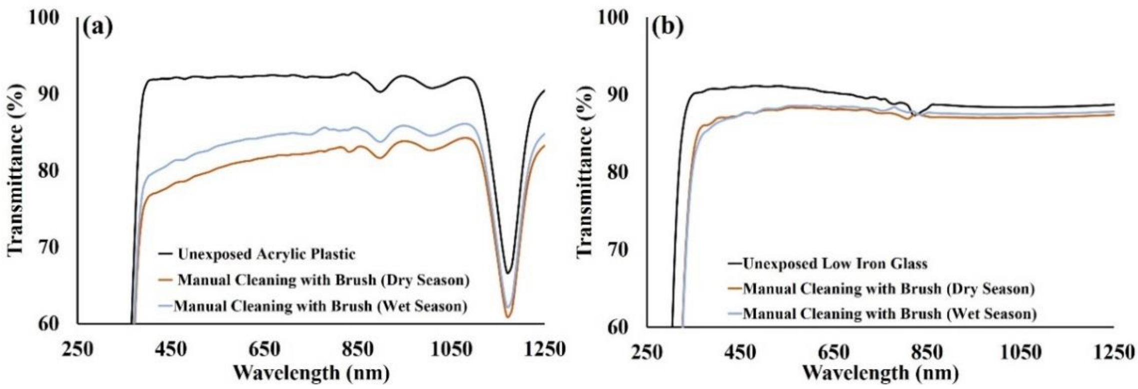


Fig. 8: Optical transmission losses variation considering the seasonal disparity of a soiled coupon with a clean one exposed under manual cleaning with brush (a) acrylic plastic, (b) low iron glass coupon.

The findings from Fig. 9 shows that this technique presented a low initial cost, high effectiveness on low iron glass, but average on acrylic plastic; the monthly cost is average in a developing country where the minimum wage is meagre. However, the technique presented a high rating in limitation and appeared to have a very low-reliability rating. Overall, based on the results demonstrated in Fig. 9, the technique is grossly inefficient as its performance is below average during the two seasons.

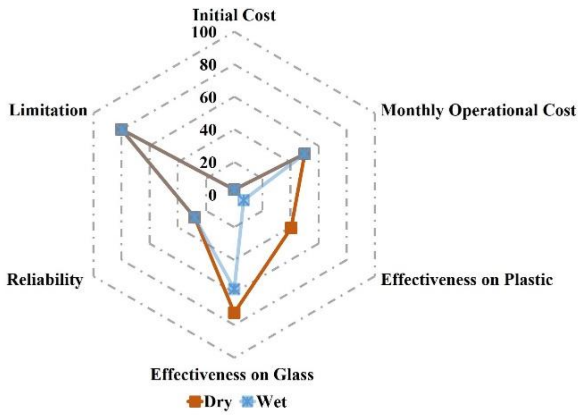


Fig. 9: Performance assessment of manual cleaning with brush illustrating cost variation, limitation, effectiveness on coupon cleaning, and reliability

3.1.3 Natural cleaning by wind and rain

As expected, a significant increment in optical losses is observed when natural cleaning by wind and rain were expected to act as a soiling cleaning technique. The results illustrated the most substantial losses in Fig. 10 shows that about 28% optical loss reduction was recorded on acrylic plastic when exposed during the dry season and about 15% during the wet season. Similarly, considerably higher optical losses were recorded on the low iron glass, with about a 15% reduction on a coupon exposed during the dry season and a 14% reduction during the wet season. There was a wide variation (10%) of optical losses between acrylic plastic coupons and low iron glass coupons exposed during the dry season. Still, a relatively small difference was observed during the wet season.

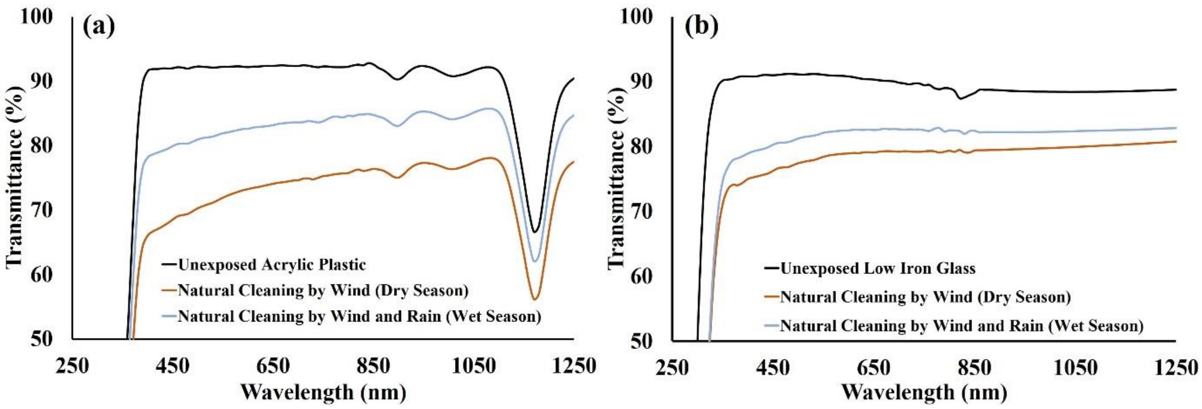


Fig. 10: Optical transmission losses variation considering the seasonal disparity of a soiled coupon with a clean one exposed under natural cleaning by wind and rainfall (a) acrylic plastic (b) low iron glass coupon.

The natural cleaning technique's assessment findings are presented in Fig. 11: zero initial cost, zero monthly cost, and effective coupons during both seasons. Conversely, the technique has a high rating in limitation and extremely low reliability during the dry season but average during the wet season. This technique's overall performance during both seasons is below average, making it an unreliable approach.

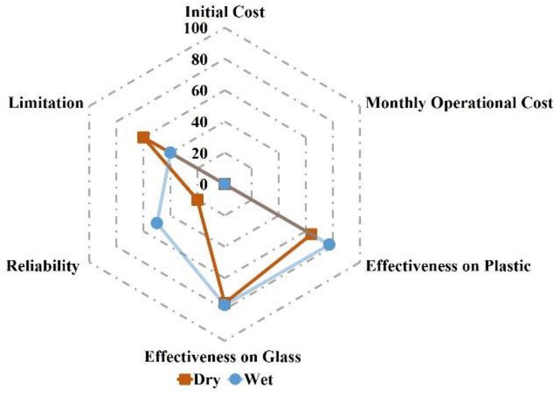


Fig. 11: Performance assessment of natural cleaning with wind and rainfall illustrating cost variation, limitation, effectiveness on coupon cleaning, and reliability

3.1.4 Self-cleaning

The optical losses of exposed coated coupons were determined using an unexposed coated coupon's optical transmittance as the benchmark instead of a clean coupon. However, Fig. 12 (a) and (b) presented the optical transmittance characterisation of a clean coupon, followed by the unexposed coated coupon and then the exposed coupons. The result from self-cleaning techniques illustrated in Fig. 11 (a) showed an optical loss of about 8% reduction when a coated acrylic plastic was exposed during the dry season and 3% on a similar coupon exposed during the wet season. On the other hand, findings illustrated in Fig. 12 (b) show that a 5% reduction was recorded on a coated low iron glass coupon exposed during the dry season. Only about 1% reduction was recorded on a coupon exposed during the wet season, the lowest losses recorded on all the exposed coupons from various mitigation techniques.

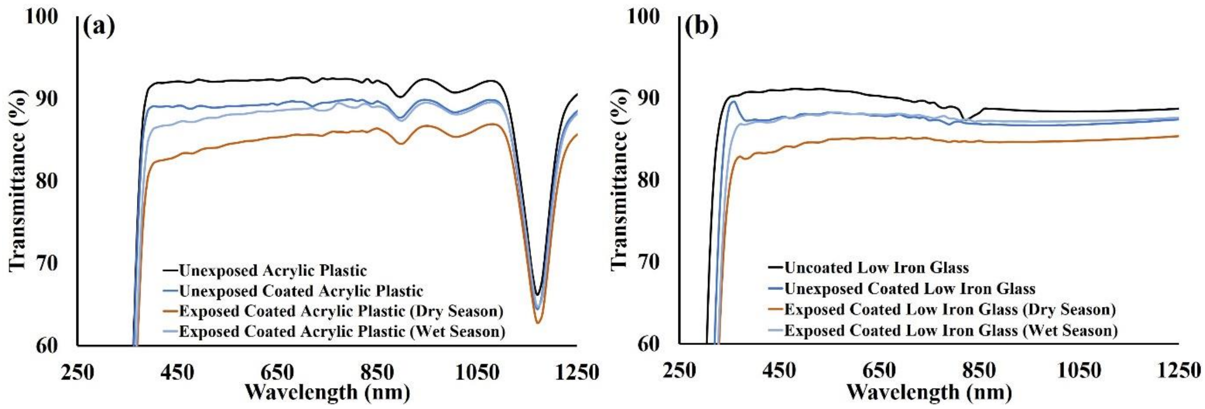


Fig. 12: Optical transmission losses variation considering the seasonal disparity of a soiled coupon with a clean one exposed under self-cleaning by hydrophobic coating (a) acrylic plastic, (b) low iron glass coupon.

This is the only technique where results are presented in two radar charts to illustrate the variation of the cost implication between tiny coupons (50 mm x 50 mm) and a 325 W polycrystalline silicon solar module (1956 mm x 992 mm). In addition, the study illustrates the comparison with a broader PV surface dimension used on the experiment site to highlight cost. The result illustrated in Fig. 13 (a) shows that the technique has a low initial cost, meagre monthly maintenance cost, appears to be effective on both coupons with a better performance during the wet season, and reliability rating is high coupons. However, a high limitation rating is presented during the dry season, and an average limitation is presented during the wet season. Therefore, the overall performance rating for self-cleaning on a coupon offered an average rating for a dry season but an above-average rating during the wet season. On the other hand, Fig. 13 (b) presented a sizeable solar module estimation that shows a low maintenance cost, high effectiveness on coupons, and a high-reliability rate. However, it comes with a high initial cost and a high rating of limitation on both coupons. Nevertheless, the overall performance based on the estimation result shows the high-performance rating on both coupons during both seasons.

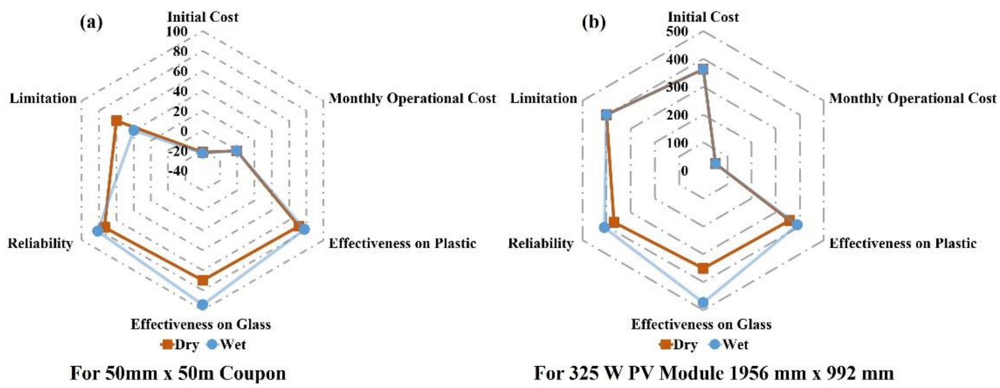


Fig. 13: Performance assessment of hydrophobic self-cleaning illustrating cost variation, limitation effectiveness on coupon cleaning, and reliability for (a) coating on 5 cm x 5 cm coupon, (b) estimation of coating on 195.6 cm x 99.2 cm PV module.

3.1.5 Mechanised cleaning

The mechanised cleaning technique's impact shows quite surprising findings where high optical losses were recorded. For example, fig. 14 (a) shows that ~9% reduction was recorded on acrylic plastic coupons exposed during the dry season and 10% during the wet season. On the other hand, the result illustrated in Fig. 14 (b) shows relative low optical losses on the exposed low iron glass coupon that were cleaned using a mechanised technique with about 5% reduction during the dry season and about 6% decrease in the wet season.

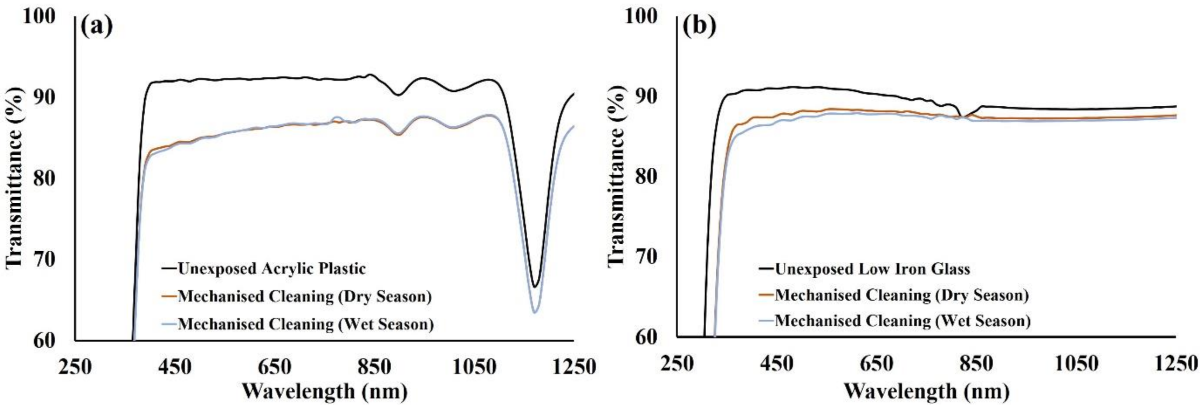


Fig. 14: Optical transmission losses variation considering the seasonal disparity of a soiled coupon with a clean one exposed under mechanised cleaning with wiper (a) acrylic plastic, (b) low iron glass coupon.

The finding for the mechanised cleaning technique shown in Fig. 15 illustrated that the technique has a low/near average initial cost of equipment required for installation. The monthly operational and maintenance cost is average in developing nations with meagre minimum wage, the system reliability during the dry season is above average. However, it is below average during the wet season; it is highly effective on both coupons during the dry season. The effectiveness appears to be above average on the low iron glass during the dry season and below average on acrylic plastic during the wet season for both coupons. However, the technique is rated high in limitation. Based on the findings presented in Fig. 15, this mitigation approach is rated as an average technique.

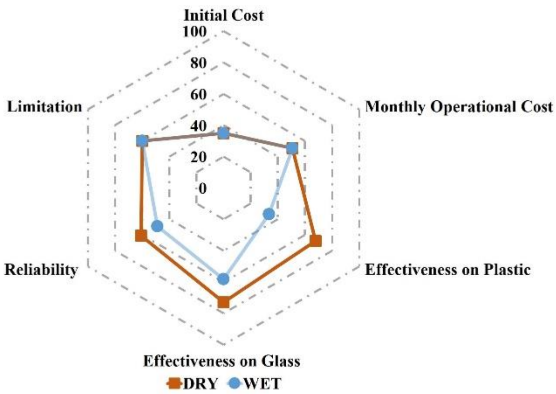


Fig. 15: Performance assessment of mechanised cleaning approach illustrating cost variation, limitation effectiveness on coupon cleaning, and reliability.

The findings are not constant, and the two variables (coupon and season of exposure) presented a considerable wide variety. However, these disparities may be subtle; however, they could lead to system performance failure over an increased length of exposure and make mitigation techniques redundant and useless. This section demonstrated optical losses and performance variations in various technique considering time stamp and covering materials. It highlighted different performance parameters considered, and its grading is for the techniques.

4 Discussion

The negative impact of soiling seems to be of particular importance, and various mitigation techniques were examined to identify the most suitable one for the region. There is no doubt that there might be a stringent criterion used to improve this approach. However, the knowledge of the optical losses is essential in determining each soiling mitigation technique's performance, and it is vital to evaluate each technique's performance since it is location dependent.

The results presented in the subsequent section shows substantial performance variation among the various mitigation techniques. Findings show that the most significant optical losses were recorded on the coupons under the natural cleaning technique during the dry season with about 28% reduction in acrylic plastic and 15% for low iron glass. On the other hand, the lowest optical loss was recorded on a glass coupon under self-cleaning during the wet season with about a 1% reduction. Thus, the technique that yielded the most favourable performance for both dry and wet season was the self-cleaning technique on a coupon; however, manual cleaning with squeegee and water presented the highest performance during the dry season with optical efficiency even greater than self-cleaning. However, the lack of maintenance of the squeegee created abrasion, and other factors (limitations) led to an overall performance drop. The self-cleaning method presented good performance during the dry season because it reduced the adhesion force by preventing the particles from reaching the coupon surfaces. The composite material reduces the Van der Waal forces since particles inter-particles adhesion and particles to surface adhesion were significantly reduced during the dry season. The coating also significantly reduces the capillary forces during the dry season, which reduced the overall soiling rate. SEM imaging was not conducted; otherwise, it would have provided significant practical finding. However, the fit is highly recommended that similar studies employ SEM imaging for adhesion forces analysis. The effectiveness of manual cleaning with water and squeegee on low iron glass was better than self-cleaning coating during the dry season, but the very low performance was recorded during the wet seasons because of the abrasion that occurs on the coupons where the greatest was observed on the acrylic plastic. The squeegee was repeated used without cleaning, and no detergent or any solution was added. The pressure of the water was also shallow, thereby allowing the squeegee to be scrubbing the dust particles (appears to be PM_{10}) on the coupon creating scratches. On the other hand, the technique that offered the lowest performance during the dry season was cleaning with a brush and mechanised cleaning for the wet season. Thus, although natural cleaning happens to deliver a high loss during the dry season, it can be observed that it is not the most ineffective during the wet season. Sarver et al. [2] supported this claim by stating that natural cleaning can sometimes be the most effective approach with zero cost.

The computational performance analysis shows that seasonal variation influences the performance disparity of the various techniques; besides, coupon type is a critical factor strongly linked to the particular technique. The analysis shows that the self-cleaning approach offers high performance on both coupons during the wet season and glass during the dry season. Manual cleaning with squeegee/water and self-cleaning have almost the same performance rating plastic during the dry season. The self-cleaning coating can suspend particle and protect the covering material, and when the water comes, it can roll it off the panel surface.

Quan et al. [22] stated that anti-soiling coating could reduce dust adhesion on a coated surface. This justifies the low accumulation on the coupon's surface, particularly during the wet season. Fig. 5 (a) shows high wind velocity during averages of >4 m/s for both season, and in addition to that heavy rainfall, was presented during the wet season, as illustrated in Fig. 5 (b). Gholam et al. [34] stated that wind velocity >4 m/s could play a critical role in determining the accumulation rate on surfaces. This supports the claim that high wind velocity plays a vital role in removing particles. It is assumed that this wind also reduces the amount of accumulated dust on coupons, so the uncleaned coupons were referred to as natural cleaning coupons. A higher rating of about 50% was recorded on a low iron glass exposed in the same solar farm in the same month but different surface orientation. The only disparity is that coupons used in this research were positioned in the North-East direction facing the incoming wind during dry season exposure (January 2020). The other coupon was exposed to the region's optimum surface orientation (0°/180°). Hee et al. [58] illustrated how an inward wind reduces accumulation on a facing coupon and more reduction in rainfall.

The findings also show techniques that did not yield the expected performance, with the worst recorded on the manual cleaning using a brush for both coupons during the wet season and on plastic during the dry season. Mechanised techniques appear to present the worst performance on glass coupon exposed during the dry season. This lesson is directly related to cleaning the coupon with a dirty brush and a dusty wiper brush. Both the brush and the wiper were cleaned at the beginning of the study but were intentional, never washed to determine if they can contribute to additional losses. Fig. 3 illustrated the mechanised platform's image before and after exposure, and it was observed that the platform and wiper blade, in particular, accumulated a significant amount of dust.

The main reason for employing glass and plastic over PV cells' surface is to protect them from harsh environmental conditions. The findings highlighted that acrylic plastic has higher transmittance levels (92%) before exposure than low iron glass (91%). These values concurred with Smestad et al. [42] and Nelson et al. [41], where the transmittance of clear low iron glass (uncoated low iron glass) was reported to be about 91%, and Total_Plastic [19] reported 92% for acrylic plastic. However, more significant optical losses were recorded on acrylic plastic coupons under all the mitigation techniques attributed to its adhesion characteristic and prone to scratches. This indicates why low iron glass remains the better option since it has less attractive forces and not prone to scratches. Sarver et al. [2] stated that, so far, glass has demonstrated to be the long-lasting serving PV covering material that is durable for the system's lifetime. The optical loss findings of a manual technique demonstrated a significant transmittance reduction during the dry season. The loss from cleaning with a brush on acrylic plastic triples the low iron glass loss. The acrylic plastic possesses three negative factors (prone to degradation due to UV, easily scratched and high adhesion force), making it a less preferable material for the arid and semi-arid region [5, 33].

All the soiling mitigation approaches investigated have few limitations, with some related to exposure location. Some presented manageable limits, while others presented an insurmountable limitation impediment. The manual cleaning with squeegee and water offered such as; requiring personnel which needs to be provided with adequate training, untrained personnel can easily break a panel or cause other damages, and maintenance staff are prone to electrocution. The manual cleaning with the brush provided limitation such as; requiring personnel which need to be provided with adequate training, abrasion could occur in acrylic, plastic, untrained personnel can easily break a panel or cause other damages, maintenance staff are prone to electrocution during the wet season if not using proper PPE (personal protective equipment). The natural cleaning technique possesses limitation such as; uncertainty, seasonal variation, particular PV orientation for optimum cleaning, might require monitoring, and might cause negative impact such as cementation when light rainfall occurs after a sandstorm. The self-cleaning mitigation possesses its limitation: seasonal dependency, high maintenance cost for large scale, the coating could only last for only two to three years [20]. Some limitations were also identified for the mechanised mitigation approach: the high cost of installation and extensive maintenance, reliability issue might arise when automated to operate with a sensor, blade requires cleaning during the dry season otherwise high level of abrasion might occur.

A number of comprehensive reviews of the various soiling technique's efficiency and performance provided insufficient procedures and performance data. Therefore, according to the application technique, a comparative summary of performance variations is presented in Table 2, Table 3, Table 4, Table 5, and Table 6Table 6.

Table 2: Summary of performance variation illustrating a comparison between this study and other published reports for the Natural cleaning approach.

<table>
<tr><th>Technique</th><th>Reported by</th><th>Requirement</th><th>Advantages</th><th>Disadvantages</th><th>Optical Efficiency</th><th>Improvement</th></tr>
<tr><td rowspan="4">Natural Cleaning</td><td>Gupta et al. [4]</td><td>• Rainfall
• Wind
• Snow
• Gravity
• PV Tilt angle</td><td>• Zero Cost</td><td>• Weather dependent
• Location dependent
• Ineffective on small dust particle</td><td>• Not Available</td><td>• Not Available</td></tr>
<tr><td>Jamil et al. [20]</td><td>• PV Tilt Angle
• Rain</td><td>• No Cost</td><td>• Dependent on-site condition
• Dependent on weather
• Only deal with large dust particles, more than 10 μm rather than smaller ones (2–10 μm)</td><td>• Unpredictable
• It could be less effective</td><td>• Superhydrophobic or hydrophobic coating to enhance performance with rain</td></tr>
<tr><td>Deb and Brahmbhatt [10]</td><td>• PV tilted to 23-25
• Rain</td><td>• Zero cost</td><td>• Weather and location-dependent;
• Only large particles</td><td>• Unpredictable
• surface property can be improvised</td><td>• Not Available</td></tr>
<tr><td>This study</td><td>• High wind Velocity
• Heavy rainfall
• PV orientation
• PV tilt angle</td><td>• Zero Cost
• It can be integrated to work with other technologies to reduce cost.
• Highly effective in regions with heavy rain.</td><td>• Weather dependent
• Site dependent
• Unreliable</td><td><table><tr><th rowspan="2">Coupon</th><th colspan="2">Season</th></tr><tr><th>Dry</th><th>Wet</th></tr><tr><td>Plastic</td><td>72%</td><td>88%</td></tr><tr><td>Glass</td><td>85%</td><td>86%</td></tr></table></td><td>• At optimal performance can be integrated with other techniques to reduce maintenance cost.
• Required monitoring to achieve high performance.</td></tr>
</table>

Table 3: Summary of performance variation illustrating a comparison between this study and published review studies for manual cleaning strategy with a brush.

<table>
<tr><th>Technique</th><th>Reported by</th><th>Requirement</th><th>Advantages</th><th>Disadvantages</th><th>Optical efficiency</th><th>Improvement</th></tr>
<tr><td rowspan="4">Manual Cleaning with Brush</td><td>Gupta et al. [4]</td><td>• Human resources
• Brushes
• Ladder</td><td>• Performed whenever required</td><td>• High labour cost
• Scratches may be developed with time</td><td>• 100%</td><td>Not Available</td></tr>
<tr><td>Jamil et al. [20]</td><td>• Workforces
• Brush
• Equipment</td><td>• Highly efficient in restoring the PV performance</td><td>• High cleaning cost
• Abrasion could be produce</td><td>• Effective in any condition</td><td>• Resource for cheap labour to reduce the cleaning cost
• The use of soft material could replace brushes</td></tr>
<tr><td>Deb and Brahmbhatt [10]</td><td>• Labour
• Equipment</td><td>• Considerably efficient in reinstating PV cleanliness</td><td>• High cost
• It could be abrasive to the PV surface</td><td>• Effective at all times
•</td><td>• Cheap labour is required</td></tr>
<tr><td>This Study</td><td>• Personnel
• Brush.</td><td>• Cheap labour in a developing country
• On-demand
• Job opportunity.</td><td>• Unreliable
• Very difficult to regain high PV performance
• Very expensive in developed countries.
• Causes abrasion</td><td><table><tr><th rowspan="2">Coupon</th><th colspan="2">Season</th></tr><tr><th>Dry</th><th>Wet</th></tr><tr><td>Plastic</td><td>83%</td><td>86%</td></tr><tr><td>Glass</td><td>95%</td><td>95%</td></tr></table></td><td>• Cleaning should be conducted with water during the dry season
• Wind direction should be determined prior to cleaning to avoid dust transfer from one module to another when cleaning dry dust.</td></tr>
</table>

Table 4: Summary of performance variation illustrating a comparison between this study and published review studies for manual cleaning strategy with water and squeegee.

<table>
<tr><th>Technique</th><th>Reported by</th><th>Requirement</th><th>Advantages</th><th>Disadvantages</th><th colspan="3">Optical efficiency</th><th>Improvement</th></tr>
<tr><td rowspan="7">Manual cleaning with squeegee and water</td><td>Gupta et al. [4]</td><td>• Human resources
• Water
• Cloths
• Detergent
• Ladder</td><td>• Effective in recovering PV Performance
• Performed whenever required</td><td>• High labour cost
• Water limitation in arid regions
• Scratches may be developed with time</td><td colspan="3">• 100%</td><td>Not Available</td></tr>
<tr><td>Jamil et al. [20]</td><td>• Workforces
• Water
• Detergent/Chemical
• Cloth
• Equipment</td><td>• Highly efficient in restoring the PV performance</td><td>• High cleaning cost
• Abrasion could be produce</td><td colspan="3">• Effective in any condition</td><td>• Resource for cheap labour to reduce the cleaning cost
•</td></tr>
<tr><td>Deb and Brahmbhatt [10]</td><td>• Labour
• Water
• Cleansing agents
• Equipment</td><td>• Considerably efficient in reinstating PV cleanliness</td><td>• High cost
• Could It could be abrasive to the PV surface</td><td colspan="3">• Effective at all times</td><td>• Cheap labour is required</td></tr>
<tr><td rowspan="4">This Study</td><td rowspan="4">• Personnel
• Water
• Squeegee</td><td rowspan="4">• Reliable and effective
• Cheap labour in a developing country
• On-demand
• Job opportunity
• Reduce PV temperature for better performance</td><td rowspan="4">• Expensive in the developed world
• Tendency of abrasion
• Prone to electric shock.
• Not feasible in areas with high water drought.</td><td rowspan="2">Coupon</td><td colspan="2">Season</td><td rowspan="4">• PPE should be used at all time to avoid electric shock
• Personnel should be provided with adequate PV maintenance training</td></tr>
<tr><td>Dry</td><td>Wet</td></tr>
<tr><td>Plastic</td><td>91%</td><td>94%</td></tr>
<tr><td>Glass</td><td>96%</td><td>97%</td></tr>
</table>

Table 5: Summary of performance variation illustrating a comparison between this study and published review studies for hydrophobic self-cleaning technique.

<table>
<tr><th>Technique</th><th>Reported by</th><th>Requirement</th><th>Advantages</th><th>Disadvantages</th><th>Optical efficiency</th><th>Improvement</th></tr>
<tr><td rowspan="4">Self-cleaning with hydrophobic Surface</td><td>Gupta et al. [4]</td><td>• Forming hydrophobic
• Chemical coating
• Water</td><td>• Requires zero power
• Improve the natural cleaning</td><td>• Limited lifetime
• Reduced the optical performance</td><td>• 71.80%</td><td>Not Available</td></tr>
<tr><td>Jamil et al. [20]</td><td>• Fabricated hydrophobic layer
• Chemical coating Water</td><td>• Passive and power not required</td><td>• Uncertain durability on plastic due to UV
• Acid rain and salty air might cause layer degradation
• Dust accumulation increases with time
• Dependent on rainfall
• High initial cost whenever applied to large scale PV system</td><td>• Moderately performance efficiency in the presence of rain</td><td>• The use of high polymer, glass or coating could increase durability
• Require cleaning during the dry season</td></tr>
<tr><td>Deb and Brahmbhatt [10]</td><td>• Hydrophobic layer
• Chemical coating or screen layer
• water</td><td>• Passive method
• Power not required</td><td>• Degradation of the plastic screen due to UV
• Dust accumulation with time
• Cleaning requires water</td><td>• Medium efficiency in rain</td><td>• Requires weatherproof surface to improve performance
• Require regular cleaning</td></tr>
<tr><td>This study</td><td>• Chemicals for Coating
• Determining transparency and hydrophobicity.
• Water</td><td>• Does not require human support during the wet season
• Passive approach
• Highly reliable during the wet season.</td><td>• Uncertain durability on plastic.
• Water dependent.
• Lifetime is very minimal</td><td><table><tr><th rowspan="2">Coupon</th><th colspan="2">Season</th></tr><tr><th>Dry</th><th>Wet</th></tr><tr><td>Plastic</td><td>92%</td><td>97%</td></tr><tr><td>Glass</td><td>95%</td><td>99%</td></tr></table></td><td>• PV manufacturing companies or glass companies should accept changing covering surface for recycling a couple of times during its life cycle.
• These techniques required integrating additional technique to support it during extreme dry, dusty weather such as Harmattan.</td></tr>
</table>

Table 6: Summary of performance variation illustrating a comparison between this study and published review studies for mechanised cleaning method.

Technique	Reported by	Requirement	Advantages	Disadvantages	Optical efficiency	Improvement
Mechanised Cleaning	Gupta et al. [4]	• Wipers • Blower • Brushes • Motors • Gears • Chains • Sensors	• Reduces labour cost • Automation • Both cleaning & scrubbing	• Maintenance requirement • Energy consumption • High capital cost	• 95%	Not Available
	Jamil et al. [20]	• Brush/Wiper Mechanical prime Mover components (motor, gears, and chains) • Robotic (optional)	• Dropping system temperature with water • Automatic activation of cleaning with sensors and controllers • Bird scaring • Decreases labour cost and increases system independency	• Abrasion due to contact with PV panels surface. • Cleaner quickly get dirty (brush and wiper) • The system requires its own maintenance • Energy consumption • High initial cost	• Useful in an uncertain time	• Cleaning schedule to be arranged when the system is not operating to avoid shock • Soft material should replace brushes and wipers • The automated motorised part could save the energy
	Deb and Brahmbhatt [10]	• Motor • Brush • Wiper • Robot (if any)	• Reduces temperature with water • Automated operation by sensors and controller • Scares birds • Less labour cost • The system can be independent	• The surface is abrasive due to direct contact with PV • Dust accumulation on cleaning material • Increase in energy consumption • Higher capital cost; • Higher maintenance cost	• Uncertain efficiency	• Cleaning frequency should be reduced to minimise abrasion • A High-efficiency motor could reduce the energy required for operation • The system required periodic maintenance
	This study	• Wiper/Blade • Electric Motor • Battery • Operational personnel or Arduino for automation	• Reduces labour cost • Can operate independently • Energy can be used obtained from the system when excess energy is available • Scares birds, rodents and reptiles	• System initial and maintenance cost is high • Required continues maintenance • Accumulated dust on the brush could cause surface abrasion.	**Coupon** / **Season**: **Dry**, **Wet** **Plastic**: 91%, 90% **Glass**: 95%, 94%	• Water injection through blades could improve cleaning efficiency during the dry season. • Blade or brush should periodically be cleaned to avoid accumulation. • Appropriate maintenance should be provided before sunrise.

It should be noted that literature used in comparison Table 2, Table 3, Table 4, Table 5, and Table 6 are obtained from review articles and not actual research were as data presented from this study are actual findings obtained through experiments. Table 2 compared the findings from examining the effectiveness of the Natural cleaning technique and other reported findings. It shows that PV orientation is a factor necessary for influencing the natural cleaning of a region. It assists when wind direction and heavy rain flows towards the module. Two vital points were provided as additional advantages observed from this study: heavy rain could be highly effective. The technique could be integrated with others to improve their performance in regions with high rain rates. The advantages appear to be almost the same, highlighting the unreliability of the technique, weather dependent, and location. The study provided optical efficiency degradation based on transmittance reduction for two seasons and considering PV surface covering material. Comparison of the manual cleaning result obtained from this study and the reported findings in Table 3 show variations and inadequate consideration of some regions concerning labour. The literature shows that the technique is costly, related to the cost implication of labour that varies between developed countries and underdeveloped. In developed countries it labour is costly while it is cheap in underdeveloped countries. This technique serves as a source creating job opportunities for the community and promoting local acceptance in under development. The efficiency of this technique has not been reported, but it is widely employed. This study provided performance level considering seasonal variation and types of coupons. Manual cleaning with squeegee and water is a widely used technique in regions with the availability of water. It improves the performance in two ways; improving transmittance and reducing temperature. These two factors could allow the generation of optimal yield. The literature is relatively silent on the impact of temperature reduction, but this study highlighted it in Table 4. The similarity observed in the performance comments where all studies presented show the technique is efficient in recovering from soiling losses. However, Gupta et al. [4] were the only ones among the literature that provided value that is not specific on the seasonal disparity and type of coupon variation. Self-cleaning provides a preventive and restoration approach, and the literature shows it requires water and performance is generally reported to moderate. However, this study shows that it is highly reliable during wet seasonal. The findings show better performance of the technique on the low iron glass compared to acrylic plastic. The disparity was observed in the performance comments, where the literature presented in Table 5 shows the technique's performance is low. However, Gupta et al. [4] were the only one in the literature that provided a higher value that is not closer to this study. The comparison table of mechanised technique (Table 6) provided similar information between literature and this study, except in performance where only Gupta et al. [4] and this study provided a similar numerical value on low iron glass coupon exposed during a dry season. Literature provided studies that proposed some improvement on the various technique. This comparative information highlighted the variation from these studies and others and illustrated the novelty of the research work.

The outcome of various experiments shows that the self-cleaning technique is the approach that exhibited the highest performance during both the wet season and dry season. The manual cleaning with squeegee and water also revealed high performance during the dry season. Although this is only a limited study, the full potential of approaches could be further investigated. However, PV modules need cleaning to sustain or restore output performance, and thus far, this study is the only outdoor research in the region. Therefore, the study recommends using a hybrid cleaning technique during the dry season where self-cleaning (hydrophobic or superhydrophobic coating) and manual cleaning with water and only self-cleaning (hydroponic or superhydrophobic coating) cleaning during the wet season for the region. Using water can improve the cleaning rate during the dry season without rainfall; it will also help reduce the temperature for better performance. The low iron glass coupon appears to be the most suitable PV covering material since it has fewer adhesion forces and less affected by UV light. This study recommends using low iron glass in arid or semi-arid regions with high solar irradiance, temperature and UV. Additional research is recommended to investigate the use of various mitigation techniques on an exposed working solar module in the arid or semi-arid region to determine their effectiveness and stability over a longer duration and a periodic frequency cycle.

5 Conclusion

Developing countries invest in solar energy to increase the penetration level of renewable energy in their supply mix and reduce climate. However, soiling has been established to cause a detrimental effect on PV performance, yet the available cleaning strategies have a significant limitation on the region of deployment. The findings show a variance of performance among different soiling mitigation techniques. The hydrophobic self-cleaning provides 99% transmittance recovery during the wet season, and manual cleaning and self-cleaning restoring 95% transmittance during the dry season. The most significant loss was recorded on an acrylic plastic coupon exposed under natural cleaning strategy during the dry season with a 28 % transmittance reduction. In addition, it was observed that high wind velocity has a more negligible cleaning effect when compared with heavy rainfall, and more cleaning frequency and observation is required in the absence of rain. The result further demonstrated that low iron glass is more durable and effective than acrylic plastic when exposed to harsh conditions.

In conclusion, the study demonstrated that self-cleaning coating could be employed as the region's primary cleaning strategy during wet and hybrid approaches, including self-cleaning and manual cleaning with water during the dry season. This could sustain the performance PV at an optimal level year-round and reduce unnecessary soiling losses, which would portray a positive image of the technology and improve its penetration in the region. Technique performance was examined using coupons. It is recommended to study each technique's performance and cost analysis on a full pledge PV panel over a longer duration in different regions, considering the factors influencing PV system performance. Nevertheless, developing a cost-effective way to produce a bi-functional coating on a solar cell cover is considered one of several urgent needs by the solar cell industry.

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Conflict of Interest

The authors declare no conflict of interest.

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Graphical abstract