Performance enhancement of solar photovoltaic (PV) module using a novel flat plate (NFP) glass cover by reducing the effect of bird dropping (BD) settlement

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Abstract
A massive bird dropping (BD) deposition on the common rectangular flat plate (RFP) of photovoltaic (PV) module is a matter of great concern in Western Rajasthan (WR) that diminish the overall energy production capacity of the system remarkably. In this research article, a prototype novel flat plate (NFP) design of a front glass cover of PV module is proposed to prevent the impact of BD settlement by the restriction of bird’s sitting/movement on the front glass cover. In this regard, the performance analysis of PV module with common RFP and newly designed NFP glass covers has been assessed at the different inclination $\beta$ ($0^\circ$–$90^\circ$). The BD accumulation onto the both glass covers was explored by the optical transmittance profiles at the different tilt angles, i.e., explained by bird movement on each flat glass surfaces. Consequently, a significant amount of output electric energy has been gained in NFP design rather than RFP corresponding to particular tilt regions TR I ($0^\circ \leq \beta \leq 25^\circ$), TR II ($25^\circ \leq \beta \leq 60^\circ$), and TR III ($60^\circ \leq \beta \leq 90^\circ$). According to the results achieved, an excellent level of improvement in average power loss, $\sim 97.85\%$, corresponding to optimal TR (III) has been detected by employing NFP glass collector.

Keywords Bird dropping (BD) deposition • PV module soiling • Novel flat plate (NFP) design • Power loss • Western Rajasthan (WR)

Introduction
The accumulation of bird droppings (BDs) on a flat plate photovoltaic (PV) collector worsens the situation that additionally diminishes the performance of a solar PV module day by day, especially in the climatic conditions of WR (N24° 37′ 00″ to N30° 10′ 48″/E69° 29′ 00″ to E76° 05′ 33″) commonly which is characterized by its “high rate of dust deposition” and “small frequency (10.4–20.5 days in a year) of rainfall with poor intensity” in a year (Singh et al. 2005). An enormous settlement of BDs and dust fouling (i.e., “soiling”) on a flat glass cover of the PV module is a critical challenge for the sustainability of output solar power generation capacity of PV systems in the Western desert region (i.e., “Thar”) throughout the year (Fig. 1).

Partial shading (i.e., non-uniform illumination) due to surrounding fixed objects like building, tower, tree, and passing clouds (i.e., dynamic shadow) is a key issue that strongly affects the overall performance and decide the life of a solar PV plant. In addition, the deposition of surrounding location and environment-related fine dust particles like as salt, plant products, debris, soot, and BD (i.e., static shadow) on the surface of PV module are promptly observed (Mekhilef et al. 2012; Appels et al. 2013; Maghami et al. 2016; Said et al. 2018; Smestad et al. 2020) in daily examples. Common soling factors like fallen leaves, BDs, and water streaking can reduce the energy efficiency up to 10–30% additionally (Dabhi et al. 2017) as well. Furthermore, the dirt deposition can be also in a main aggressive form of the
biological contamination “BD.” Therefore, it is commonly pointed out that BDs (guano) is one of the main contaminated source of soiling on PV systems that reduce a more electric energy output (Kalogirou et al. 2013; Cano et al. 2014; Xu et al. 2017; Hanifi et al. 2019). In this context, it has been widely noticed that perching birds carry small dust particles and dropping matter sediment by their feet and body (Reheis and Kihl 1995). When sunlight strikes on a front glass plate of PV module, it absorbs, scatters, and reflected back by dirt particles and drastically reduces the intensity of transmitting light that incident on the active portion of the PV module (Yfantis and Fayed 2014; Pedersen 2015). In feature, BD matter is fairly opaque and can adversely affect the optical performance (i.e., transmission of sunlight) of the PV system (Ghazi et al. 2014; Ghosh and Neogi 2016; Bingöl and Özkaya 2018). A thick layer of accumulated BD matter is an example of uneven soiling that leads to hard shading conditions on PV system and it forms static shading that concerns to localized degradation of PV modules (Wohlgemuth et al. 2013; Pettersen 2015). Furthermore, the affected portion of the PV glass cover persists shaded for long time until washed properly (Sayyah et al. 2014). As Bana and Saini (2017) demonstrated the effects of shading caused by various obstacles such as bird litters, tree, pillars and passing clouds consider the mimetic of 14 different kinds of shading patterns. At coastal sites of Lebanon, the presence of birds (seagull) is mainly caused by waste dumps in that region (Hammoud et al. 2019). Harrison et al. (2017) discussed the impact of solar farms on birds, bats, and general ecology. Moreover, Babatunde et al. (2018) commented the significant effect of BD fouling on PV plant (B-Block), i.e., installed at the tilt angle of 15°. It is mostly seen that the impact of BD settlement is incredibly cruel than soiling due to fine dust particles and other contamination sources. Hence the practically, complete removal of strongly adhered BD from system surface will be almost cost effective, particularly for the large-scale PV sites (Al-Jawah 2014).

In another work, 2% reduction in maximum power ($P_{\text{max}}$) has indicated exposure to outside BD conditions (Lmenes et al. 2011). Over time, if BD materials are not properly scrubbed on the module surface, heating of the particular shaded area starts may lead to discoloration and as a result permanent damage appears in the form of hotspots (Chaudhary and Chaturvedi 2017). In thermo-graphic study of PV module, Sharma and Jain (2016) inspected the effects of hotspots, cracks, and BDs on PV system. In addition, it is also pointed out that the BD material is much more opaque than other soiling contents like dirt, pollen, and dust. With this regard, high instantaneous loss 81% of PV systems with high BD accumulation was noticed in Chandler, AZ, whereas high soiling condition concerned with the great amount of BD deposition, in the absence of regular rain event for a long time, close to horizontal plane, and low cleaning frequencies (Naeem 2014). The consequences about the effect of BD settlement on PV system have been summarized as in Table 1.

### Bird’s repelling systems

Nowadays, a number of efforts have been developed for terrifying and preventing the birds sitting on PV module in...
various aspects. A number of measures have been employed for scaring and terrifying the birds such as bird spikes, audible bird scares, low-current electric barriers, and nontoxic chemical products (Ballinger 2001; Tate 2010; Hudedmani et al. 2017) widely in practice as listed in Table 2.

A mechanized cleaning (robust structure) system is often used to scare off BD material (Deb and Brahmbhatt 2018). In the context of cleaning process, an active self-cleaning system that removes contamination from a PV glass plate is based on microsized features and mechanical vibration (Sun and Böhringer 2020). Lamont and Chaar (2011) has also designed a mechanized cleaning (robust structure) system is often used to scare off BD material (Deb and Brahmbhatt 2018). In the context of cleaning process, an active self-cleaning system that removes contamination from a PV glass plate in various tilt angles in different seasons (Chanchangi et al. 2020).

Table 1  General summary of the impact of BD settlement on the PV module performance worldwide

| Authors               | Key points                                                                 | Main results                                                                 |
|-----------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Sun et al. (2014)     | I-V characteristics of shadow by small BD area                              | \( P_{mp} \) drops 1W FF drops 1%                                             |
| Lee et al. (2018)     | I-V and P-V characteristics of each configuration corresponding to different BD shadow patterns | The power generation is greater for parallel configuration rather than series connected |
| Niazi et al. (2019)   | Thermal effect of PV module                                                 | 50–60 °C (without shading) 69 °C (with shading)                               |
| Sisodia and Mathur (2019) | Electrical performance of PV system in various tilt angles in different seasons | Power loss 14.2% (0° ≤ \( \beta \) ≤ 25°) 6.2% (25° ≤ \( \beta \) ≤ 60°) 9.7% (\( \beta \) > 60°) |
| Mustafa et al. (2020) | Transmission reduction of bird droppings on various types of coupons        | 90% for acrylic plastic 54% for low iron glass 87% for acrylic plastic 75% for low iron glass |
| Vumbugwa et al. (2020) | Power reduction                                                            | Reduce the output power by about 7.4%                                        |

Table 2    Evaluation of some common different kinds of bird repelling systems

| BD preventing system | Key points                                                                 | Evaluation                                                                 | Authors                                                                 |
|----------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------|
| Spike system          | Metal/polycarbonate spikes attached to the upper side of metal frame of PV module | • Self shadow of spikes and nesting on PV glass cover (Lamont and Chaar 2011) Metal spikes supports to decrease greatly on the bird droppings on the PV modules (Cano et al. 2014) | Lamont and Chaar (2011)                                                 |
| Scare crow            | Installed near the PV module                                                | • Eventually, some birds get used to scarecrow and resume their sitting habits on the neighboring objects (Król et al. 2019) | Lamont and Chaar (2011)                                                 |
| Electronic repeller   | Ultrasonic sound-based system fixed with the PV module                      | • Helps in irritating and scaring the birds. More numbers of repellers are required for larger PV plants (Pandiyan et al. 2019) | Lamont and Chaar (2011)                                                 |

and sitting on PV module as shown in Fig. 2(b) (Mondal and Bansal 2015; Król et al. 2019). In general, a very common tactic is used for keeping the birds away from the device, installing either metal or polycarbonate spikes on the metal frame of PV module as presented in Fig. 2(c) (Cano 2011; Naeem 2014).

As above mentioned, it can be commonly seen that only the limited work has been attended in context to the prevention of BD contamination on the PV glazing surface worldwide so far.

**Common shadow effect by bird’s movement and BD deposition**

Numerous types of common shadow effects are to be associated with the birds sitting/walking tenacity and their impact of BD deposition habit on the PV module surface in different aspects, i.e., responsible for diminishing the sunlight transmittivity by negative effects such as “the covering by BD deposition” (i.e., blocking the sun radiation by covered area), “dynamic shadow caused by bird’s movement” (i.e., by sitting/walking of birds on the front PV glass surface and its metal frame also), “self-shadow of dropping materials,” and due to “splashing of urine fluid slope down to the PV glass surface” as illustrated in Fig. 3.

Moreover, settled bird’s poop material strongly attracts the smallest dust particles and promotes more dust accumulation...
on over itself that leads to more power loss and as final result, critically disturbs the panel’s operational life and its DC power output. For this purpose, the characterization study regarding the effect of BD deposition on PV front glass cover is essentially part of the study in understanding about the poop.

**Characterization of BD material**

There are mostly found shapes of BD material (i.e., scoop, circular tube, and flatter pattern) and sizes (~3–6 cm) deposited (i.e., strongly stuck) in bulk amount over the smooth glass surface of PV module as shown in Fig. 4. The bird’s fecal matter is mainly composed of quartz (SiO$_2$) with some alkali and alkaline earth metals.

**Scanning electron microscopy–energy dispersive spectroscopy analysis of BD**

In the detailed characterization study of fecal matter, the morphological and elemental analysis is performed using a scanning electron microscopy–energy dispersive spectroscopy (SEM-EDX) (BRUKER) technique. The dried BD sample is collected from PV glass surface and then material is ground
using an agate mortar pestle to obtain the samples in the form of fine powder. A route diagram of sample preparation for the characterization is shown as in Fig. 5.

Concerning study depicts the vulnerability and the role of bird’s dropping elements in adhesion of matter to PV glass surface. The images of SEM-EDX analysis of collected BD material from the PV module glass plate have been presented in Fig. 5. The obtained results of SEM-EDX analysis indicate that BD sample contains the most common found elements in poops (guano) as alkali (Na, K) and alkaline (Ca, Mg) earth structures in which larger particles are enveloped by small needle fabrics, and their typical EDS spectra of adhesive BD particles.
metals mixed up with some other elements such as aluminum (Al), iron (Fe), and silicon (Si). The presence of Si (small dust particles) confirms that the bird intake small pieces of stone (pebbles) in their diet. Moreover, the presence of small dust particles in depositing fecal matter leads to itching (i.e., *scratching of PV glass surface*) the smooth glass surface during regular cleaning process of PV glass surface. A long-time effect results in an increase of the blurriness (optical aberration) of the glass surface and hence reduce the intensity of sunlight across a PV module glass surface. All these particles are randomly allocated and a “needle like” structure is examined in the SEM results that attributes to the formation of humidity containing soluble or partially soluble deposited BD material became dried up (i.e., *cementation of matter*) (Mehmood et al. 2017; Ilse et al. 2018a, b). These structures attribute the tendency of link (i.e., adhesion by air moisture capturing) between the dropping particles and PV glass surface primarily made by needles (Ilse et al. 2016).

Once the hydrated BD material gets dries under the action of sun heating then it becomes hard (sticky) and difficult to remove from the smooth glass surface of PV module as a result of *cementation* process (i.e., *strongly adhered to the solid glass surface*) as depicted in Fig. 6 (Sarver et al. 2013; Hassan et al. 2016). In practice, the water-dissolved ions (Na⁺, K⁺, Ca²⁺) attract undissolved BD’s particles (semi-solid) due to electrostatic and ionic bonding force and increasing adhesion strength (Adukwu et al. 2020). These ions enter into the hydrated layer of BD matter and hold them together during the water evaporation under the action of sun heating (Yilbas et al. 2015; Abdelmajid 2016; Yilbas et al. 2017). At the same time, action of surface tension concerns to the interaction between the BDs and present water molecules in void space of the solid matter is to be deposited over the glass surface of panel. This effect concerns the meniscus forces which produces the dust cluster and scales up the adhesion strength in between the dust particles and PV glass surface (Cuddihy 1980; Kempe 2006; Moutinho et al. 2017).

**Dropping cleaning time (removal time of BD components)**

It is mainly seen that the fecal material is more adhered to the glass surface of the PV module rather than dust particles, even though a vacuum cleaner is also not able to remove (i.e., can’t easily detach the solid poop’s matter from smooth glass surface) the BD material from the glass surface of PV module (Boeing 2018). Sometimes, a rigorous rain event cannot be enough to wash away the BDs from glazing surface of PV system completely (Cano 2011; Solórzano and Egido 2013; Thevenard and Pelland 2013) and as such, electrical performance losses due to BDs cannot entirely restore after small rainfall events (Kumar et al. 2013). Therefore, a regular wet or dry manual cleaning of PV glass surface is essentially needed. Hence, the BD deposition may have some serious effects comparatively to dust settlement (Mani and Pillai 2010). Consequently, the great amount of water will be demanded either by manual or automatic cleaning for complete removal of the strongly adhered dropping matter from the PV surface. As an approximate assessment, 10 gal of water is required for the cleaning work in about 15 min. The estimated water consumption is to be 1.98 liter/m² (Naeem 2014).

Therefore, in order to check out the adherence (stickiness) of dropping material to the smooth glass surface, a simple lab test is conducted in the laboratory for simulating the effect of cleaning time of various adhered phases of BD matter due to rain event as shown in Fig. 7.

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**Fig. 6** Schematic diagram of adhesion process (i.e., cementation) of BD material under the action of sun heating on PV glass surface

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With this regard, it is usually observed that in the beginning of cleaning process, initially deposited dust particles are removed and then less sticky green part of BD material is to be easily detached from the smooth glass surface, while white creamy part (i.e., dried uric acid, $C_5H_4N_4O_3$) more adhere with the glass surface) is still adhered with the glass surface and it takes much more time to wash off completely from the PV module plate as shown in Fig. 8.

It is commonly seen that the birds excrete nitrogenous wastes in the form of uric acid (viscous and mucoid) and it does not easily dissolve in water (Balogh 2017). Hence, its capability to stick onto the PV module glass cover strongly like drops of white plaster. Uric acid is a heterocyclic compound of carbon (C), nitrogen (N), oxygen (O), and hydrogen (H); and the pH level of uric acid lies in between 3.0 and 4.5 (quite acidic) (Vasiliu and Buruiana 2010; Wanda 2010). In which, the pH level matter also affects the adhesion process significantly, i.e., adhesion strength between the accumulated solution (i.e., white paste of hydrated BD matter) onto PV glass surface varies with the pH of the solution (Somasundaran et al. 2005).

As well as this, it is commonly evident that white creamy part of acidic BD material stays even (i.e., strong adhesive) on the panel’s surface after a rigorous rain event for a long time.
Eventually, it is almost predicted that an appropriate intensity of rainfall is frequently required to clean the complete PV module glass cover from soiling off.

As an overall, a high-intensity level of rainfall will be continuously required to clean up the entire module glass cover. Meanwhile, in the case of dust removal, only a less amount of rainfall is needed. Especially in winter season, a very little rain event quickly promotes the BD accumulation during the period from October to February (i.e., critical BD deposition period/Winter) in WR and can cause extensive power drop in this time period.

**Experimental methodology**

**Description of novel design structure**

Currently, installation of a regular RFP collector technology at fixed tilt angle and orientation in portrait mode is very common in practice worldwide. The occurrence of biological BD contamination on the front glass collector of a PV module is a crucial factor, especially in a desert zone which leads to an additional reduction in power generation capacity of PV system. For solving this problem of BDs, a prototype NFP design of the front glass surface has been proposed for reducing the effect of BD deposition on a novel flat plate glass cover as depicted in Fig. 9.

![Fig. 9 Schematic diagram and digital photograph of side and backside structure of proposed NFP collector for preventing the bird sitting/movement](image)

In newly designed structure (NFP), the following steps have been considered for reducing the adverse effects of BD settlement on PV glass surface based on restricting the sitting/movement of birds on the smooth front glass cover:

(i) In first step, the upper side of a PV glass plate has to be shaped into an isosceles triangle for avoiding the “bird sitting” on it. For this specific designing purpose, the internal angles ($\theta$) of both equal sides of the triangle kept minimum as $\sim 45°$ are considered (Fig. 9). This particular side angle of $\theta$ ($\sim 45$) will support to constraint the bird’s sitting/movement on upper angled sides, especially at high inclination $\beta$ ($>60$) of the plate.

(ii) In addition to the first step, around $\sim 5$ cm of the upper glass strip of equal angled sides is kept free from back support for maintaining only the thickness of the glass plate ($\sim 2$mm) as shown in Fig. 10a. For thin glass strip, metallic and some other polycarbonate type hard materials can be used on the place of glass optionally. The key usefulness of this idea is to prevent the “gripping of a bird’s claw” with upper angled sides of the smooth thin glass strip and its result is that birds will be unable to sit on it (i.e., slip down). In general, it is mostly pointed out that all common RFP PV modules is bounded by a $\sim 1$mm thick, L-shaped aluminum metal frame with $\Gamma_V$.
vertical component of ~3.5cm which offers an appropriate space for the bird’s movement/sitting along the upper side of the metal frame at the high inclination as presented in Fig. 10b.

Electrical performance analysis

In an experimental measurement, a reduction in output power of PV system caused by BD settlement has been assessed. In

Fig. 10  a Photograph of the proposed NFP design structure shows front, back, and side view (~5-cm glass strip around equal sides is to be free from back support is shown by yellow ribbon). b Common RFP design (i.e., L shape) offers a support for the easy (free) movement of birds along the straight upper side of aluminum metal frame in which vertical component ($\Gamma_V$) of aluminum frame serves as base space for bird’s movement at the high inclination particularly
this regard, we have considered a set of transparent glass plates of the RFP and NFP design structures for the output electrical power assessment. These glass plates (i.e., RFP and NFP) were exposed to BDs at different tilt angles (TA) in a natural outside experiment condition for the PV performance evaluation. For this purpose, eleven identical ~2-mm-thick RFP- and NFP-designed glass covers were considered for the experimental investigation. The glass plate collectors were fixed with eleven TA (β) (0° to 90°) at 10° increments from horizontal to vertical position, where the TA of glass cover considered from the horizontal direction. In interest, one of the glass plates is placed at a specific angle, approx. 25°5′ (common yearly), which is the optimum fixed tilt angle of the PV module installation in WR. All glass covers were fixed on a wooden-based structure of different inclinations (0° to 90°) as shown in Fig. 11.

### Electrical experimental description

The experimental work is completed by attaching the exposed BD glass plates to a reference solar PV module (40-W, Ritika RSPL12P40) as shown in Fig. 12. The test PV system comprises of a standard silicon solar module of area 2511 cm² (15.5 cm × 4.5 cm/array of 36 series connected cells as 9 × 4 serial configuration strings) and the professional solar wattmeter (Solar Module Analyzer PROVA 210) is used for assessing the PV output. Output electric data collected every week is frequently measured under the natural sunlight for the evaluation of PV output. The data were recorded manually with a clean module glass cover and after that with an exposed BD plates.

A full experimental study was executed on a terrace of building located in the Jodhpur region (26.91° N, 70.90 E/WR) over a time of 4 months (from December to March) during critical BD deposition period (i.e., a Winter season). After deposition of fecal material (i.e., exposed glass plate of the RFP and NFP at different inclination) on a glass collector, the monthly average data have been collected as fast as likely on clear shiny (sunny) days. As result, the outcome of BDs can be assessed in term of power losses (%) by comparing maximum output power $P_{\text{max}}$ (i.e., $P_{\text{mpp}}$) before (clean/without BD) and after (dirtied/with BD-exposed glass plates) contamination by using Solar Module Analyzer PROVA 210 stated as follows (Sulaiman et al. 2014; Sun et al. 2014) and as presented in Fig. 13.

$$\Delta P(\%) = \frac{P_{\text{max, out}}(\text{clean}) - P_{\text{max, out}}(\text{bird dropping})}{P_{\text{max, out}}(\text{clean})} \times 100$$  \hspace{1cm} (1)

### Optical performance analysis

In optical performance analysis, the normal transmittance measurement across the BD-contaminated novel designed glass structure has been assessed. As a result, the “BD pattern” (i.e., the spatial distribution of BD deposition) has been obtained for demonstrating the effect of BD settlement over the RFP and NFP glass plates at different inclinations. In this regard, the intensity of transmitting light across the dropping-contaminated NFP glass samples was studied using a solar power meter. In this method, the exposed glass plates were exposed at the different TA (β), from low inclination (horizontal/0°) to high inclination (vertical/90°) directed, for 4 months from December to March (winter) (Nahar and Gupta 1990; Elminir et al. 2006; Sisodia and Mathur 2019).

### Optical experimental description

The optical performance is evaluated by the transmittance measurement (i.e., transmittance profile) of BD-contaminated NFP glass design. The normal transmittance measurements through the contaminated glass covers were
carried out in the laboratory with the experimental setup as shown in Fig. 14a. The experimental setup consists of a yellow halogen light (equivalent to sunlight) source of visible spectra (555 nm) range, convex lens, and dirtied glass plate samples, patterned in square-shaped section (patch) of area (4cm×4cm). Concerning this, the average transmittance intensity $\Delta T (%)$ of halogen light (W/m²) was measured by using a MECO solar power meter (Rao et al. 2014; Sisodia and Mathur 2020) across to each patch as depicted in Fig. 14b. A significant fall in intensity of transmitting radiation causing the bird’s dropping can be calculated by the output transmittance losses (%) as follows:

$$\Delta T(%) = \frac{T_{\text{clean}} - T_{\text{bird dropping}}}{T_{\text{clean}}} \times 100 \tag{2}$$

The influence of BD settlement on transmittance losses (%) corresponding to RFP and NFP structures at different TA($\beta$)

In this regard, an average transmittance loss ($\Delta T$%) with the location (i.e., area of plate) on the RFP and NFP exposed samples has been plotted (i.e., called “BD profile”) corresponding to different TRs (i.e., I, II, and III) to describe the effect of spatial settlement of BD on to the RFP and NFP glass covers. In fact, obtained transmittance profile depicts the direct results of the bird’s movement (i.e., sitting/walking behavior) on the flat glass surface as shown in Fig. 15a–c.

Results and discussions

As considered experimental results, the effect of BD settlement on RFP- and NFP-designed structures has been represented by an output electrical study (i.e., power loss, $\Delta P$%) at the different TA ($\beta$). Afterward, these obtained results were also explained by the transmittance study (i.e., transmittance losses, $\Delta T$%) of BD deposition patterns (settlement of BD on the flat glass cover space, i.e., dropping pattern) categorized corresponding to three different inclined regions (i.e., a region TR I, TR II, and TR III).

The effect of BD deposition on RFP and NFP design structures on solar power output (%) with different TA ($\beta$)

The effect of BD contamination on the RFP- and NFP-designed structures has been determined in terms of average power losses ($\Delta P$%) at different TA ($\beta$). The obtained results show a significant reduction in output power loss (%) due to BD phenomena onto the set of eleven TA ($0°$ to $90°$) for both designs (i.e., RFP and NFP). The particular observed results and study can be analyzed into three specific TRs corresponding to different inclinations, i.e., a TR I ($0°$ to $25°$), TR II ($25°$ to $60°$), and TR III ($60°$ to $90°$) as indicated in Fig. 16.

In TR I ($0°$ to $25°$), it is pointed out that a critical reduction in output power has been observed for both types (i.e., RFP and NFP structures) of contaminated glass cover at the inclination $0°$ (i.e., close to horizontal way) due to great deposition...
of BD material rather than other tilt configuration listed as in Table 3. Moreover, it is also fairly pointed out that almost the same average power losses have been detected for both design structures, i.e., 19.21% for RFP and 19.17 for NFP. Because, in this horizontal position of glass cover, birds can easily move/walk over entire the surface area in the same manner on the both plate structures. Now with TR II (25° to 60°), a significant change in average power loss has been noticed, i.e., 19.21 to 9.77% for RFP and 19.17 to 2.67% of the NFP glass surface across the border of TR I/TR II, i.e., $\beta$° (~ 25), which is termed as “threshold tilt angle ($\beta_{thr}$)” as shown in Fig. 16. In TR II, a 9.77% reduction in the RFP design has been measured while 2.67% for NFP design structure. In contrast, it is well noticed that a suitable improvement (2.67%) in output power has been detected out for NFP design structure as compared to the RFP design (9.77%). Finally, a very good progress has been observed 2.67 to 0.316% for NFP glass cover across the boundary of TR II/TR III. Meanwhile, a great power loss has been again progressing 9.77% to 14.68 for the RFP glass plate which is explained by the tendency of bird’s sitting/movement at the upper side of the common RFP surface. Because, in RFP, it widely noted in nature that birds have always a common habit to walk/sit along the upper straight side (i.e., towards the slop up side) and the traditional

Fig. 13 Estimated $\Delta P(\%)$ corresponding to different inclination ($\beta$°) for the bird dropping-contaminated RFP and NFP glass surfaces
aluminum frame (L shape) of PV module offers a suitable space where they can simply grip the metal frame edge at any inclination ($\beta$°) as shown in Figs. 10b and 17.

**Bird movement (BD process) on NFP-designed glass surface at different inclinations ($\beta$)**

It was definitely seen that the different obtained “BD patterns” of the RFP and NFP glass plates at different slopes $\beta$ are described as the tendency of bird’s movement over the front glass surface of PV module. In this regard, it is also commonly noticed that birds have the general tenacity to easily walk on the flat surface and move towards the slope up side. Moreover, they also like to sit where they can easily grip the object by their claws (Isaksson 2008). A significant difference in technical characteristics (i.e., output power and transmittance) has been noticed in between both design structures (RFP and NFP) which was explained by the BD deposition phenomenon on both types of glass covers. Hence, the outcome regarding the phenomenon of BD contamination over NFP and RFP designs is directly associated with the walking/sitting tendency of bird on the surface which is characterized as follows:

**Close to horizontal plane (small inclination)/TR I ($0^\circ \leq \beta \leq 25^\circ$)**

In this tilt region, an utmost BD stores on the entire PV glass surface of the RFP and NFP designs. In this regard, it is widely noticed that birds are capable to simply move over the entire glazing surface without any restrain and hence, resulting the random deposition of BDs in the same manner on the complete glass cover of the RFP and NFP designs. In this situation (TR I), the same response of birds has been noticed corresponding to both glass covers (RFP and NFP). Because in this inclined region, bird’s movement should be regardless of the shape of flat plate. Hence, an almost relatively similar reduction in average output power loss ($\Delta P\%$) has been evaluated 19.21% and 19.17% for RFP and NFP designs respectively in TR I. A BD deposition phenomena and their corresponding exposed NFP design glass plate are illustrated in Fig. 18.

**Above-threshold inclination (moderate inclination)/TR II ($25^\circ \leq \beta \leq 60^\circ$)**

As inclination changes from TR I to II (i.e., across the boundary, $\beta$: 25°), now the BD accumulation starts to fall rapidly due to confinement of bird’s movement (i.e., a restriction of bird’s movement) on the RFP and NFP glass collectors. A significant fall in average output power loss from 19.21 to 9.77% and 19.17 to 2.67% respectively for the RFP and NFP design glass surface has been observed across the first boundary of the TR I/TR II. As result, it is clearly observed that a good improvement in output power production has been achieved by employing the NFP rather than RFP design at the moderate inclination (region II), where power loss cuts 9.77% (RFP) to 2.67% (NFP) respectively as depicted in Table 3. Therefore, the main advantage by employing NFP design is a well improvement “72.67%” in output power reduction achieved in this moderate inclination (i.e., TR II).

An abrupt fall in observed power loss (%) is explained by a different sitting/walking behavior of birds on the front glass surface.
cover. In this condition, a few BD deposition are localized only on the upper side of the front glass surface. In this contrast, it is usually seen that birds have more chance to sit at the top edge (i.e., birds try to sit at the tip of the plate) of the

Fig. 15 Transmittance profiles demonstrating the effect of BD deposition (i.e., spatial settlement) onto RFP- and NFP-designed structures: a at 10° (region I, i.e., close to the horizontal plane); b at 40° (region II, above threshold); and c at 80° (a region III, i.e., close to the vertical plane)
NFP glass plate, i.e., above the angle of $\beta$ ($\approx 25^\circ$) (threshold inclination), birds start to slip down to the glazing surface, and they try to move towards the “upper side” (i.e., towards the slope upside) of the plate as expected by their habit (i.e., birds are always likely to sit at the apex of the object). As result, the falling fecal material is only concentrated (localized) at the top edge of the angled sides as depicted in Fig. 19.

Meanwhile, in the case of common RFP glass cover, the birds are confined to move along the complete upper straight edge of the PV plate. Hence, the obtained dropping pattern consequently appears as a strip-like shape (2–5 inch approx.) on the upper side of PV surface rather than NFP design and the result is that more sunlight is blocked on the upper side of the RFP glass design of module as illustrated in Fig. 17.

Moreover, in the scenario of NFP structure, a significant improvement is seen due to its specific design and construction in comparison to the RFP design. In NFP design, the bird’s movement is to be more restricted in comparison to sitting behavior on the RFP design. In the following, due to specific structure of NFP glass surface, birds are only capable to sit at the top of the plate (top of the isosceles triangle due to slope made by internal angles ($\theta$) of two equal sides, i.e., minimum $\theta \approx 45^\circ$) at the moderate inclination.

Consequently, birds will contaminate only the small area ($\approx 16 \times 22$ cm$^2$) of a flat glass cover at the top of the plate as shown in Fig. 19. Hence, its result to a considerable improvement in output power production has been detected in this TR II. This small contaminated area will be same for any size of the NFP glass cover.

Close to vertical (at high inclination)/TR III ($60^\circ \leq \beta \leq 90^\circ$)

In the study, the most important part is the high inclination ($60^\circ \leq \beta \leq 90^\circ$/close to vertical) region. In this tilt part, once again, more BD settlement takes place onto the RFP photovoltaic surface in which BDs slip down and traverse a long distance due to gravitational effects. Concerning this, BD covers the complete glass surface of the PV system in a specific settlement pattern (i.e., vertically long strip-like shape) and its result is that power loss again increases from 9.77 to 14.69% in the case of common RFP glass cover at the high inclination.

But in the case of NFP collector, a very insignificant amount (i.e., almost nil BDs) of BD deposition has been traced out on glass surface due to its specific designing and construction during the experimental period. Consequently, a very small average power loss $\approx 0.316\%$ has been recorded at the high inclination (i.e., TR III) for a particular plate design (NFP). Hence, the novel design surface works best effectively at the high inclination, i.e., particularly in the region III ($60^\circ \leq \beta \leq 90^\circ$) due to its explicit design of front glass plate rather than common RFP design surface of PV module.

According to this specific design, internal angles ($\theta$) of two equal sides, i.e., minimum $\approx 45^\circ$, offer well slopes on both equal sides of an isosceles triangle which is able to restrict the bird’s movement only on the top edge of an NFP glass plate at high inclination. In addition to this, one sees that a strip around $\approx 5$ cm on the both upper equal sides of an

### Table 3  Average power reduction (%) of RFP and NFP design structures at different TRs

| Design | Average power losses $\Delta P$ (%) |
|--------|-----------------------------------|
|        | Region 1 ($0^\circ$ to $25^\circ$) | Region 2 ($25^\circ$ to $60^\circ$) | Region 3 ($60^\circ$ to $90^\circ$) |
| RFP    | 19.21                             | 9.77                              | 14.69                              |
| NFP    | 19.17                             | 2.67                              | 0.316                              |
isosceles triangle is free from back support for maintaining only up to the thickness of the glass (i.e., blade like strip). It is made especially for avoiding the gripping of a bird’s claw to upper slanted edges of the glass plate design as shown in Fig. 20. As a result, with the help of this explicit novel design structure, birds are not able to sit at the tip of the thin glass plate, i.e., the perching birds have been strongly restricted in this TR III (i.e., close to vertical).

It is also commonly known that the sun is lowest in the sky during the winter and higher in summer and energy dropping on a PV module surface can considerably be improved by a suitable change in the plate inclination ($\beta$). It is, therefore, the monthly optimum tilt angle of a PV module that is maximum in December (winter) and minimum in May–July (end of summer) in WR as shown in Table 4 (Agarwal et al. 2019; Jamil et al. 2016). According to observed behavior and study concerning the NFP design, it works more successfully at the high inclination $\beta$ (> 60). As mentioned above, the optimum tilt angle is maximum in winter. As above mentioned, the particular design (NFP) will be most appropriate in winter.
season (i.e., also critical BD settlement period in a particular zone) at higher slope to be honest.

The reduction in average transmittance $\Delta T$ (%) is measured across three different inclined regions: (a) TR I ($0^\circ \leq \beta \leq 25^\circ$) range from 23.6 to 42.6% (RFP) and 20.7 to 42.4% (NFP); (b) TR II ($25^\circ \leq \beta \leq 60^\circ$) range from 21.1 to 24.9% (RFP) and 4.1 to 7.1% (NFP); and (c) TR III ($60^\circ \leq \beta \leq 90^\circ$) 29.5 to 37% (RFP) and 0.5 to 0.8% (NFP) corresponding to both glass plates of PV module respectively as shown in Fig. 21.

A substantial difference in PV losses (%) and transmittance losses (%) for RFP and NFP designs with the inclination ($\beta$)
confirms the difference in the effect of BDs on both types of flat glass covers of photovoltaic modules and proves the utility of NFP design. Finally, it can be concluded from the above observation and study of the front NFP glass collector, it works well at the high inclination especially. Hence, the optimal inclination for NFP design $\beta^\circ$ has the minimum power loss, “0.316%” which is corresponding to TR III ($60^\circ \leq \beta \leq 90^\circ$) definitely. The obtained results of this research work will be helpful for reducing the impact of BD accumulation on the front glass cover of PV module in the solar field.

**Conclusion and recommendations**

This research work has been performed to investigate the effect of biological BD contamination and how it can achieve the performance enhancement by deploying the NFP structure reducing the BD accumulation in outside environmental conditions without any external consideration. The outcome of this research work shows that a remarkable amount of output power losses (%) has been improved by the application of a novel designed (NFP) structure as compared to common rectangular design (RFP). A relative analysis of output technical characteristic, i.e., output electric power (power losses %) and normal optical (transmittance loss %/dropping patterns) performance in a combination of different tilt angle $(\beta)$, has been performed to understand the phenomena of BD deposition on both types of the glass covers.

The whole experimental study concerning to RFP and NFP designs has been classified into three different TRs as the low inclination (i.e., close to horizontal/TR I), moderate inclination (i.e., above-threshold angle/TR II), and high inclination (i.e., close to vertical/TR III) explained by the sitting/walking behavior of birds on both types of glass plate structures. As stated in the case of traditional RFP design, a maximum average power loss (%) and transmittance reduction (%) has been recorded corresponding to TR I, then the minimum in TR II, and it again increases in TR III. But in the case of NFP design structure, it decreases continuously with the inclination, i.e., the performance of PV module will improves well with the inclination of plate from horizontal $\beta^\circ (0)$ to vertical $\beta^\circ (90)$ progressively.

Based on observed results, it is inferred that a considerable amount of power loss has been reduced corresponding to “72.67%” in TR II ($25^\circ \leq \beta \leq 60^\circ$) and especially at high inclination “97.85%” in TR III ($60^\circ \leq \beta \leq 90^\circ$) by employing a NFP design structure in preference to the common RFP glass plate which really proves the effectiveness and suitability of

| Table 4  | Monthly optimum tilt angle $(\beta^\circ)$ for Jodhpur (WR)/India (Yadav and Chandel 2018) |
|---|---|
| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Seasons | Winter | Summer | Monsoon | Winter |
| Tilt $(\beta^\circ)$ | 56 | 45 | 30 | 11 | 0 | 0 | 0 | 4 | 22 | 40 | 54 | 58 |

![Fig. 21 Reduction in average transmittance (%) with different tilt angles $\beta$ (deg.)](Fig. 21)
scientific values of NFP structure at the high inclination. It is, hence, the optimal inclined region is TR III (60° ≤ β ≤ 90°) for which the minimum power loss (0.316%) has been recorded due to the least effect of BD deposition on NFP design. In NFP design, the less amount of bird dropping deposition on front glass cover will improve overall performance of device and require less cleaning. Finally, from the experimental study, the following chief recommendations have been planned about the NFP design for their paramount importance as follows:

- First, in this part of NFP, the upper side has been shaped into an isosceles triangle with the internal angle of both sides should be minimum as θ~45° for constraint the bird’s sitting/movement on the angled upper edges.
- Additionally, around a ~5 cm of the upper glass strip of equal angled sides is kept blank from back support for maintaining only the thickness of the smooth glass plate (~2mm) to prevent the “gripping of a bird’s claw” with upper angled sides of the smooth thin glass strip.

Hence, a remarkable reduction in average power losses (∆P%) for NFP glass surface rather than the common RFP design confirms the effectiveness of the newly designed structure to be honest. The consequences of this research study will be useful for improving the PV performance and system life in the field of solar energy installations in outside environmental conditions.

**Author contribution** 1. Corresponding author (Anil Kumar Sisodia): experimentation work, data analysis, and manuscript preparation.
2. Co-author (Ram Kumar Mathur): supervision and data analysis.

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**Data availability** All data generated or analyzed during this study are included in this published article.

**Declarations**

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