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Development and Testing of a Low-Concentrating Photovoltaic-Thermal Collector

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Abstract. Testing and certification of solar technologies are crucial to characterize and guarantee their performance under different operating conditions. These procedures are even more relevant for novel solar technologies such as low-concentrating photovoltaic-thermal (LCPV-T) collectors. This paper presents the development and early-stage testing of a LCPV-T collector in a newly established testing laboratory based on a comprehensive review of international standards. The testing facility was designed, built, and commissioned in the north of Mexico, and it is the first of its kind in Latin America. It allows us to evaluate the thermal and electrical performance of LCPV-T collectors with a maximum area of 6 m^2 and electrical peak power of 3 kW$_e$. The operational temperature of the LCPV-T collectors can reach up to 120°C and can be characterized under steady-state and quasi-dynamic testing conditions.

Keywords: Concentrating Photovoltaic/Thermal, Performance Testing Laboratory, Solar Energy, Steady-State, Quasi-Dynamic.

1. Introduction

Photovoltaic-thermal (PV-T) collectors are a hybrid technology that combines photovoltaic (PV) and solar thermal systems. These collectors can simultaneously generate electricity and heat, increasing their efficiency to convert solar energy to useful energy for an industrial, commercial, or residential application. Low-concentrating PV-T (LCPV-T) technologies are particularly interesting for industrial applications where higher temperature levels (below 150°C) are required [1]. Testing and certification of PV-T collectors are essential to ensure their performance and reliability by providing transparent and comparable information that increases final users' trust in the technology. International standards organizations, such as the International Electrotechnical Commission (IEC) and the International Standards Organization (ISO), provide specific testing procedures and certification schemes depending on the type of collector considered (thermal or photovoltaic.). Nevertheless, currently, no standards specifically target the performance evaluation of PVT collectors.

The testing procedures typically involve measuring, analysing, and estimating the performance and robustness of solar technologies under different weather and operational conditions. This type of testing aims to obtain the thermal and electrical efficiency of different solar collectors and test its reliability. Few studies have reported the development of testing facilities for solar technologies; most of them approach remote triggered laboratories [2–4], which could be helpful to the widespread access to this type of facilities worldwide. Nevertheless, there is a lack of understanding of how this type of performance testing should be developed and the limitations of currently available standards, especially for characterizing the performance of PV-T collectors.

This paper presents the development and early-stage testing of a LCPV-T collector in a newly established performance testing facility in Mexico. Since the currently available standards only approach either solar thermal collectors or PV panels separately, this paper also aimed at identifying the protocols and procedures that could be considered for testing the performance of PV-T collectors, and at updating previous studies that reviewed testing standards for CPVT collectors [5]. The laboratory can test novel LCPV-T collectors up to 6 m^2 of aperture area and 120°C on the fluid side. This laboratory is the first of its class in Latin America. It will help the widespread adoption of hybrid solar technologies in the region by providing the necessary facilities and procedures to evaluate and ensure their performance through reliable results. The methodology presented in this work aims to review the international standards currently available to identify their limitations to support the standardization and adoption of hybrid solar technologies.

2. Methodology

The performance testing of the novel LCPV-T collector comprises the development of a laboratory following a systematic methodology: i) review of relevant international standards for thermal and electrical performance testing; ii) identification of the testing requirements parameters and metrics to be evaluated; iii) selection of equipment and instrumentation for testing; and iv) construction, commissioning, and testing.

2.1 International standards

Currently, there is a significant gap in the characterization of PV-T collectors due to their hybrid nature and the implications of ensuring the reliability of the results. For the thermal part of the system, ISO 9806:2017 [6] is the most common guideline for assessing solar thermal collectors by defining their reliability, durability, safety, and performance. Installation characteristics, type of days (weather conditions) for testing, required parameters, Instrumentation, and testing procedures are stated in this standard. Two testing methods, steady-state (SST) and quasi-dynamic (QDT), are presented as guidelines for running the necessary experiments to obtain the instantaneous thermal efficiency curve that can be compared with other collectors. Both methods require testing for at least four fluid inlet temperatures spaced evenly over the operating temperature range of the collector. For the SST method the following requirements are required [6]: the inlet temperature must be maintained within ±0.1 K [6]; the hemispherical solar irradiance at the plane must be greater than 700 W/m^2, and the diffuse irradiance levels must be less than 30%. The measurement periods must be at least four times the time constant of the collector or not less than 15 min.

QDT requires variable weather conditions. The standard recommends having four types of days to attain enough variability during the collector testing. The most important characteristics of each day are the inlet temperature of the collector and sky conditions. Test days are characterized as follows: collector temperature near the ambient temperature and clear sky (Day 1), high temperature of the collector or near to ambient temperature and partially cloudy conditions (Day 2), medium temperature of the collector and clear sky (Day 3), and high temperature of the collector and clear sky (Day 4). The inlet temperature must be kept within ±1 K during each sequence (day), and t[6]he measurement period should be at least 30 min [6].

The flaw in this standard is that it fails to address the peculiarity of hybrid PV-T technologies in detail. For PV-T collectors, the ISO 9806 standard only requires that the PV module is working at its maximum power point (MPP) so the stagnation of electrical current in PV cells does not overestimate the heat production. Moreover, thermal stagnation testing preconditioning cannot be achieved for hybrid collectors without totally or partially damaging the PV module, given the high temperature that the PV cells will reach during testing.

For the electrical performance evaluation, ISO 9806 does not specify any procedure for electric performance testing. Hence, the standard IEC 62670-3; Photovoltaic concentrators (CPV) - Performance testing - Part 3: Performance measurements and power rating [7] is taken as a reference to that end. This Standard focuses on the characterization of the electrical behavior of the collector by stating the required variables and conditions to achieve comparable overall output power. Testing consists of calculating the temperature coefficients for the efficiency of the PV cells by covering and uncovering the collector for a fast I-V curve tracing at stable Direct Normal Irradiance (DNI). Also, to infer the cell temperature at Concentrator Standard Operative Conditions (CSOC) and Concentrated Standard Test Conditions (CSTC), a dark I-V measurement at 25 °C is required. Moreover, it is necessary to achieve an acceptance angle (minimum full angle through which the collector can rotate while still producing 90% of its output) for the collector when aligning it with the tracking system. Direct normal spectral irradiance must be measured in at least three distinct ranges of wavelengths. Limitation comes for one-axis tracking concentrators due to the lack of adjustment in a secondary axis. In addition to this, the Standard establishes the requirements under which the collector should be tested. CSOC (700 to1100 W/m^2 DNI range and 0 to 40°C temperature range) works as a data retention criterion to filter the data after it was collected and allows for a standard comparison between CPV systems (including multijunction arrays) due to the fluctuation in weather conditions.

2.2 Testing facility design

The design of the testing facility is based on a comprehensive review of the standards, specifically the ISO 9806 and the IEC 62670-3. The variables to be measured and the equipment necessary to operate the laboratory were defined based on the standards and on technical characteristics of the LCPV-T collector. Table 1 shows the variables to be measured and the instrumentation required to do so.

Table 1. *Variables and instruments of the laboratory.*

Variable	Instrument	Brand	Uncertainty
HTF temperatures	RTD (PT1000)	JMI	1.5% FS
PV cell temperatures	Thermocouples (Type J)	Omega	1.5% FS
Ambient temperature	Temperature probe (HMP110)	Vaisala	±0.2 °C
Volumetric flow	Flowmeter	Omega	2% FS
GHI	Pyranometer (SMP3)	Kipp&Zonnen	2% FS
DNI	Pyrheliometer (NIP)	Eppley	1% FS
Wind speed	Anemometer (QS-FS01)	-	1% FS
Pressure	Differential pressure	Omega	0.25% FS
Electric current	Current transmitter (20A)	Ohio Semitronics	0.25% FS
Voltage	Voltage transmitter	Ohio Semitronics	0.1% FS

Since during the thermal performance test guidelines all the measurements should be taken while the electrical power generator (PV modules) works at its maximum power point. The solar charge controller or inverter connected to the PV modules should have a maximum power point tracker (MPPT) to achieve its peak electricity generation point.

The laboratory comprises hot side (variable speed) and cold side (fixed speed) centrifugal pumps, hot (300 L) and cold (3000 L) storage tanks, electric heater (15 kW), diverting valves (solenoid), single-axis sun tracking system (active), plate heat exchanger, and a microinverter (APSystems YC600B). The data acquisition system is a Compact Rio (Crio 9064).

2.3 Performance assessment procedure

To characterize the performance of PV-T collectors, the instantaneous thermal and electric power of the collector should be calculated. The thermal power is obtained with the heat transfer fluid (HTF) temperatures (T_{out}, T_{in}), the mass flow rate $\dot{m}$, and the HTF properties at a given temperature (cp, ρ). The electrical power delivered by the PV module is obtained with the measured current (I) and voltage (V). The thermal ($\dot{Q}$) power is calculated directly in LabView with Equation 1. Also, electrical (P) power is calculated as the product of measured voltage and current. In the latter case, this value is also measured directly at the microinverter.

$$\dot{Q}[W] = \dot{m}\, c_p \ (T_{out} - T_{in}) \tag{1}$$

The instantaneous thermal and electrical efficiencies are determined based on the measured direct normal irradiance (DNI) with equations 3 and 4, respectively. The thermal performance of the LCPV-T collector is finally characterized as a function of the reduced temperature (T_{rd}), (Equation 5 and 6), where T_m is the average temperature between the inlet and the outlet of the collector and T_a is the ambient temperature. η_0 is the zero-loss efficiency, a_1 and a_2 are the heat loss coefficients (W/m^{2}K^1) and the temperature dependence of the heat losses (W/ m^{2}K^2), respectively. These coefficients are determined using multi linear regression (MLR).

$$\dot{P}[W] = V.I \tag{2}$$

$$\eta_{th} = \frac{\dot{Q}}{DNI\ A} \tag{3}$$

$$\eta_e = \frac{P}{DNI\ \ A} \tag{4}$$

$$T_{rd} = \frac{T_m - T_a}{DNI} \tag{5}$$

$$\eta_{th} = \eta_0 - a_1 T_{rd} - a_2 DNI (T_{rd})^2 \tag{6}$$

The electric performance could also be characterized as a function of the reduced temperature. Nevertheless, since the performance of the PV modules depends on the PV cell temperature, this variable is considered to define the electric performance. This approach requires that the PV cell temperature is measured or indirectly determined.

3. Results

3.1 International Standards limitations

ISO 9806 and IEC 62670-3 present rules for various types of solar collectors, photothermal (solar thermal), and photovoltaics, respectively. However, each technology has boundaries that do not allow them to practice these procedures during testing. This fact is even more relevant for PV-T collectors given that, until today, no standard explicitly addresses the performance testing of this type of technology. For the thermal performance assessment, the quasi-dynamic method has been widely adopted and used for testing [8–11] since it allows more flexible testing than the steady-state method. Additionally, QDT allows for determining thermal capacity and separating beam and diffuse irradiance.

For the optical characterization, larger incidence angles (θ) lead to more significant reflection losses. The incidence angle modifier (IAM) is specified to be experimentally obtained and calculated by one of the two methods (two-axis tracking and inclination adjustment). Still, the case of one-axis tracking, as in most parabolic trough collectors (PTCs), is completely excluded from the scope, requiring additional calculations and data manipulation. Regarding the tracking system axis, Day type 1 and 2 incidence angles are impossible to achieve entirely in the case of a one-axis tracking collector. However, for day type 2, it is possible to make it work in the alternative way of handling high temperatures in the collector. Nonetheless, cloudy conditions can introduce noise in collected data and harm the PV array by shading the cells in the collector. The importance of the acceptance angle cannot be overstated, as it plays a crucial role in guaranteeing the optimal performance of the collector. However, achieving this can be challenging in systems that are either one-axis or stationary.

The measurement procedures and guidelines stated by the IEC are relatively simpler to comply with for the electric performance characterization. However, it is essential to consider the maximum power point of the photovoltaic module while selecting the appropriate microinverter and measuring instrument. The current, voltage, and power are crucial parameters to consider when selecting the equipment. In addition, accurate I-V curve tracing could be challenging since it requires measuring the PV cell temperature. Depending on the design of the LCPV-T collector, this could be an intrusive task since the thermocouples will need to be installed inside the hybrid receiver. As an alternative, thermal imaging can be used with an adequate measuring procedure and uncertainty assessment. The distribution of the temperature measuring points is also crucial. The hybrid receiver shall display varying temperatures along its longitudinal axis due to the heating of the heat transfer fluid as it flows through the receiver.

Finally, it is vital to consider the temperature threshold that photovoltaic cells can withstand to prevent potential harm to the PV module. Therefore, a maximum temperature must be defined before testing. Lastly, fluid circulation must always be active when testing under solar concentration to avoid overheating and damaging the receiver and the photovoltaic system.

3.2 Laboratory commissioning

The LCPV-T testing laboratory was designed according to international standards and consists of actuators (i.e., pumps, solenoid valves, sun tracking system), sensors (temperature, flow, wind speed, current, voltage, irradiance), and a data acquisition system. A piping and instrumentation diagram (P&ID) for performance testing of the LCPV-T collector is shown in Figure 1.

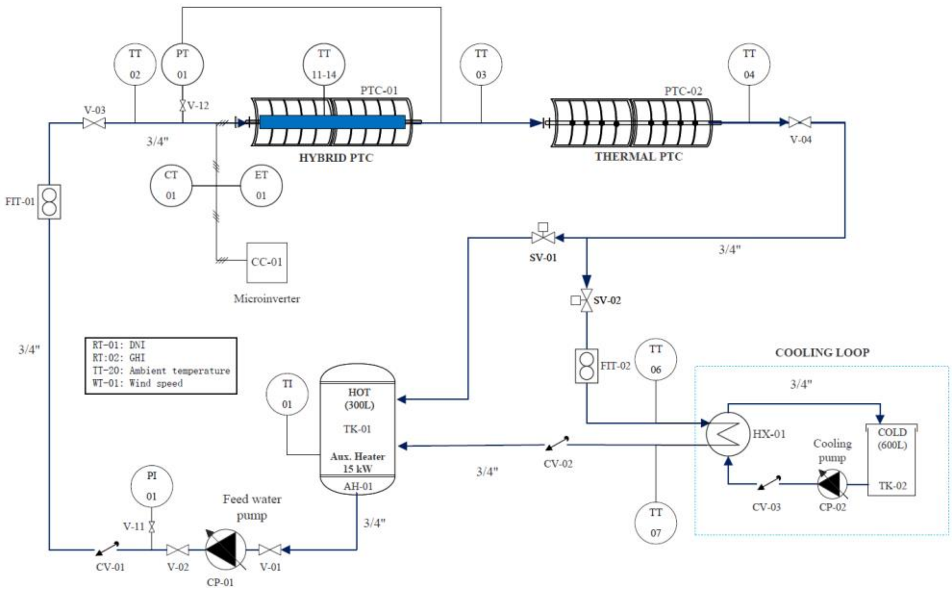


***Figure 1**. LCPV-T laboratory P&ID.*

The laboratory (Figure 2) allows thermal performance testing based on steady-state and quasi-dynamic procedures of concentrators with a maximum aperture area of 6 m^2. The photovoltaic array is connected to a microinverter with a maximum power point tracker to avoid any thermal performance overestimation. Electrical production is obtained by measuring the array's output current (IMP) and voltage (VMP) at its maximum power point. The temperature of the PV cells is also measured through contact thermocouples that can be placed along the axial axis of the hybrid receiver. The testing facility allows testing the performance of different innovations at the hybrid receiver and can measure the electrical power of PV arrays up to 3 kW_e.

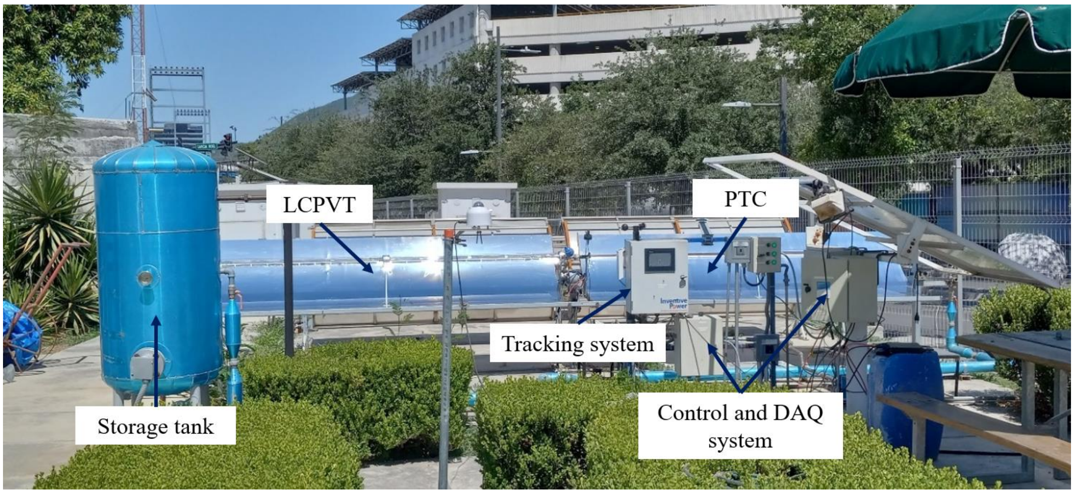
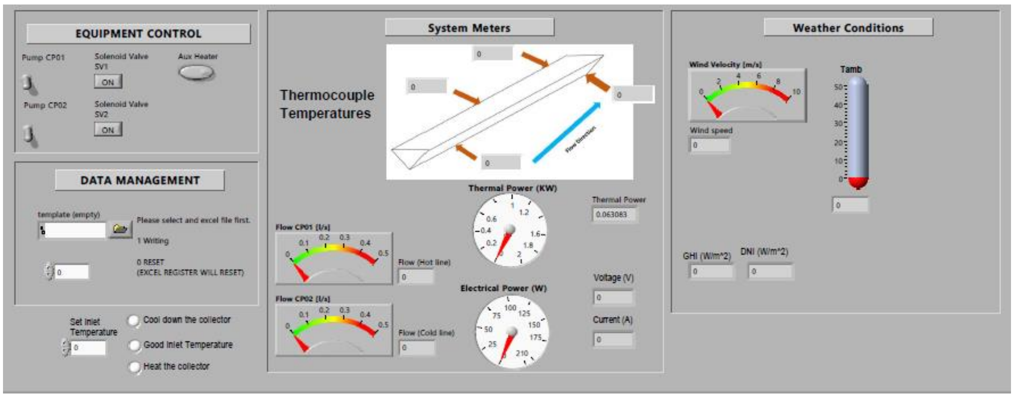
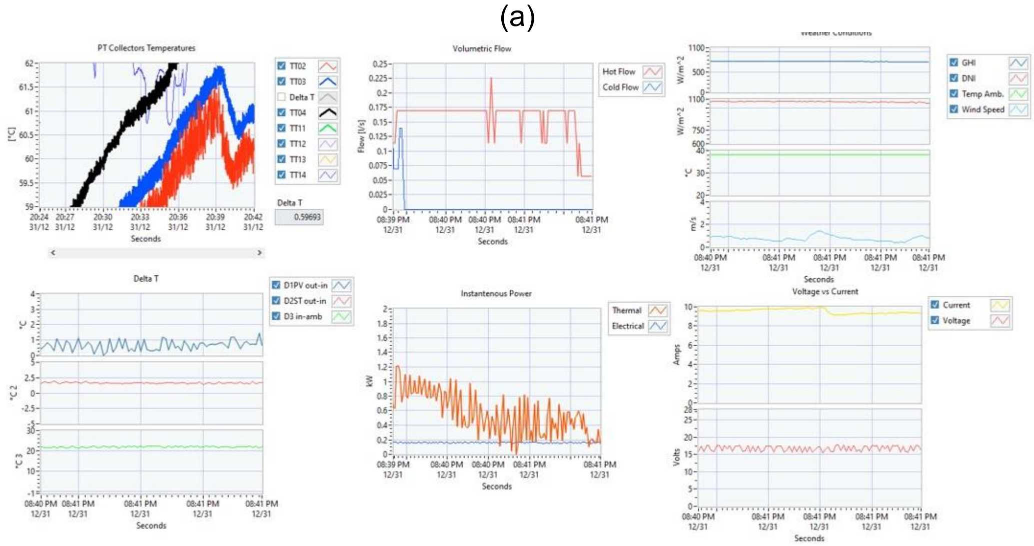


***Figure 2**. LCPV-T performance testing.*

A human-machine interface (HMI) for remote monitoring was created in LabView. The HMI is divided into real-time control, and parameter monitoring tabs. In the first tab (Figure 3a), actuators such as pumps and solenoid valves can be operated, and all measured variables are monitored while the second (Figure 3b) features real-time plots of the system temperatures (heat transfer fluid, PV cells, ambient), flow rates, thermal and electrical power, and irradiance.



(a)



(b)

***Figure 3**. LabView Visual Interface to monitor and control the LCPV-T system's variables.*

The experimental results obtained during a first testing campaign of an unglazed version of the LCPV-T collector were processed to obtain the thermal efficiency curve and compared with theoretical curves determined using a 1D thermal model (**Figure 4**). This model is based on the thermal resistance and energy balances methodology and incorporates all the heat transfer mechanisms. Further details about the model can be found in [12].

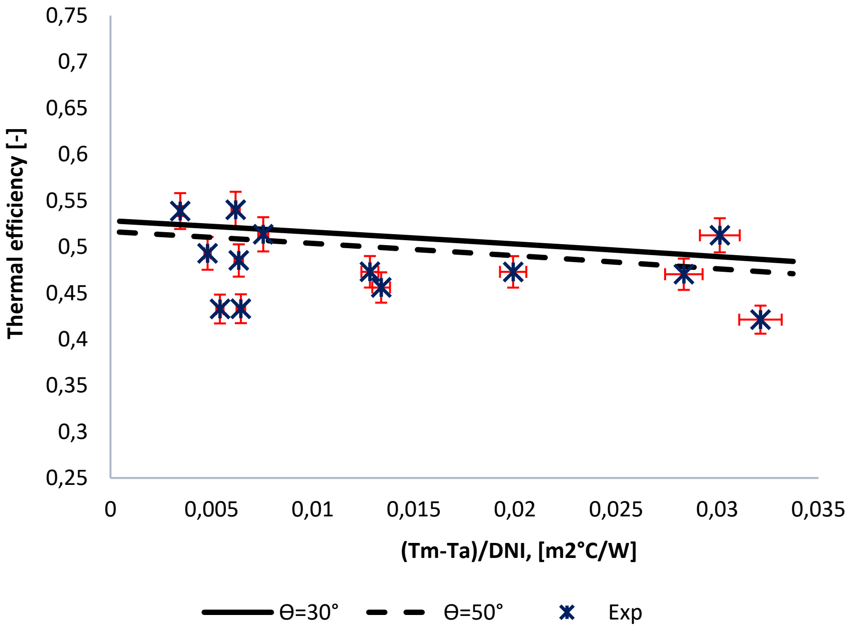


Figure 4. *LCPVT instantaneous thermal efficiency (theoretical vs. experimental).*

4. Conclusions

The performance testing of a novel LCPV-T collector was approached in this work. To that end, a laboratory was designed, built, and commissioned in the north of Mexico. The testing facility can test LCPV-T collectors (tracking and non-tracking) with aperture areas up to 6 m^2, at temperatures up to 120 °C, and electrical power generation up to 3 kW_e, which is particularly suitable for concentrating hybrid collectors.

An extensive review of the international standards and their hybridization is an intensive task that may be extrapolated to similar cases while expecting global organizations to address the problem. The revision of these documents allows us to see limitations in the design and take into account that they may be extrapolated to similar collectors from the presented laboratory. These considerations allow for more precise and reproducible testing for the reliability of the results and their comparison with other technologies by leveling the basis. From the review and the analysis of these standards, the following recommendations are provided. Stagnation conditions should be avoided due to the damage they might cause in PV cells at high temperatures for long periods. Also, cloudy conditions, as required by the Day 2 sequence, are limiting when obtaining data due to the shading in PV cells. Moreover, MPPT can be either simple or complex to get depending on the PV array design, so it is recommended to pay strong attention to its parameters when designing the collector electrical connections.

Future work will target installing a direct spectral irradiance sensor and tracker to measure DNI in different wavelengths. With this addition, there is a potential opportunity for certifying hybrid solar collectors in Mexico based on the testing procedures and international certification schemes identified and developed in this work. The novel LCPV-T collector will be further tested to obtain the electric instantaneous efficiency curves. The hybrid collectors can be compared with their thermal equivalent design in terms of aperture area.

Data availability statement

Data will be made available on request.

Author contributions

Iván Acosta-Pazmiño: Conceptualization, Methodology, Validation, Formal analysis, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Rafael García-Ramos**: Methodology, Software, Investigation, Data curation. **Chandan Pandey:** Writing – review & editing, Formal analysis. **C. Rivera-Solorio**: Writing – review & editing, Resources, Supervision, Project administration, Funding acquisition, **M. Gijón-Rivera**: Conceptualization, Writing - review & editing, Funding acquisition. **Christos N. Markides**: Writing – review & editing, Supervision, Project administration, Funding acquisition.

Competing interests

The authors declare that they have no competing interests.

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