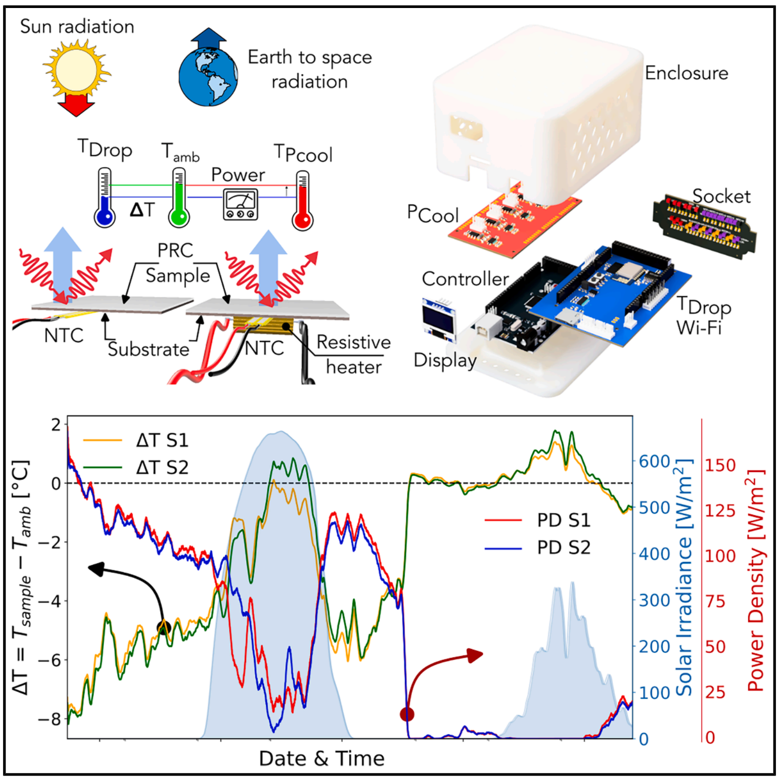
# Open-hardware platform for synchronous performance testing of multiple passive radiative cooling materials

Cell Reports
Physical Science

Article

# Open-hardware platform for synchronous performance testing of multiple passive radiative cooling materials

## Graphical abstract




## Highlights

- FRESCO-board is an open platform for testing passive radiative cooling materials
- Continuous cooling power and temperature drop measurements for multiple samples
- Measurements settings and real-time data stored locally and transmitted to mobile application
- Comprehensive environmental parameter monitoring via low-cost off-the-shelf components

## Authors

Jérémy Werlé, Roberto Concas, Ernesto Pini, Diederik S. Wiersma, Lorenzo Pattelli, Giuseppe Emanuele Lio

## Correspondence

diederik.wiersma@unifi.it (D.S.W.),
l.pattelli@inrim.it (L.P.),
giuseppe.lio@nano.cnr.it (G.E.L.)

## In brief

The rapid development of radiative cooling materials demands accessible, comprehensive, and rigorous performance assessment. Werlé et al. present an open-hardware platform based on low-cost off-the-shelf components, allowing for continuous measurement of the cooling power and the temperature drop of multiple radiative cooling materials at the same time. This offers live data streaming and user-friendly monitoring of ambient and sky conditions across multiple days.

Werlé et al., 2025, Cell Reports Physical Science *6*, 102688
July 16, 2025 
https://doi.org/10.1016/j.xcrp.2025.102688

CellPress

Cell Reports
Physical Science

CellPress
OPEN ACCESS

Article

# Open-hardware platform for synchronous performance testing of multiple passive radiative cooling materials

Jérémy Werlé,[1,2] Roberto Concas,[2] Ernesto Pini,[1,2,3] Diederik S. Wiersma,[1,2,3,5,*] Lorenzo Pattelli,[1,2,*] and Giuseppe Emanuele Lio[1,3,4,*]

[1]European Laboratory for Non-Linear Spectroscopy, 50019 Sesto Fiorentino, Italy
[2]National Institute of Metrology (INRIM), 10135 Turin, Italy
[3]Department of Physics, University of Florence, 50019 Sesto Fiorentino, Italy
[4]Present address: Nanoscience Institute – CNR and NEST Labs at Scuola Normale Superiore, 56127 Pisa, Italy
[5]Lead contact
*Correspondence: diederik.wiersma@unifi.it (D.S.W.), l.pattelli@inrim.it (L.P.), giuseppe.lio@nano.cnr.it (G.E.L.)
https://doi.org/10.1016/j.xcrp.2025.102688

## SUMMARY

The growing interest in passive radiative cooling (PRC) poses a pressing need for standardized and accessible methods to compare the performance of different material. Here, we report on the development of FRESCO-board, a low-cost, open-hardware platform providing continuous monitoring of temperature drop ($T_{Drop}$) and net cooling power ($P_{Cool}$) for multiple PRC materials at the same time. The proposed platform is further equipped with multiple sensors monitoring ambient temperature, humidity, solar irradiation, and sky temperature, an important and yet rarely measured quantity that is strongly correlated with the instantaneous radiative cooling performance. An integrated display and Wi-Fi module allow streaming real-time data to a web application or a Grafana dashboard linked to the InfluxDB database. The availability of a portable and affordable testing platform can streamline access to this multidisciplinary research field, enabling research groups to develop and compare new materials, gaining insights into their performance under different in-field conditions.

## INTRODUCTION

Energy crises and global warming represent significant challenges faced by today's world, with cooling systems accounting for 15% of global electricity consumption and contributing to 10% of global greenhouse gas emissions.[1] Consequently, there is a growing demand for energy-efficient cooling solutions, driving increased interest in zero-energy technologies to achieve carbon neutrality. A major opportunity in this area is provided by the spontaneous radiative cooling of emissive surfaces exposed to the sky. Due to the presence of an atmospheric transparency window in the wavelength range between 8 and 13 μm, a clear sky can act as an infinite and renewable heat sink, able to dissipate arbitrary amounts of thermal radiation from objects on the Earth's surface emitting within this wavelength range. This process allows them to potentially reach temperatures at or below the ambient level, thus exerting a net cooling power. As a zero-energy refrigeration technology, passive radiative cooling (PRC) has been known for millennia, but its application was mostly limited to nighttime hours until 2014. In their pioneering work, Raman et al.[2] demonstrated a multilayer photonic structure reaching a sub-ambient stagnation temperature 5°C below ambient temperature under 850 W/m$^2$ direct solar irradiation. Since then, significant progress has been made in this field, with new materials offering enhanced durability, scalability, and sustainability.[3,4] This rapid growth, however, poses the problem of testing different materials and comparing their cooling performances despite the different weather and climatic conditions under which they are evaluated.[5–8] While some groups are working toward the indoor testing of these materials inside depressurized and/or cryogenic test chambers,[9] in-field testing is still essential for assessing the expected cooling effect under real-world conditions and represents the vast majority of tests reported in the literature. Ideally, such outdoor tests should monitor a minimum set of environmental parameters, including ambient air temperature and humidity at an appropriate height from the ground, properly shielded from solar and thermal radiation.[10] Additionally, the instantaneous infrared (IR) downwelling irradiance from the atmosphere plays a key role in determining the radiative heat balance of the PRC emitter. Moreover, environmental conditions inside the test enclosure holding the samples should also be monitored and compared to the external temperature to identify deviations between the two during the 24-h cycle.[11,12] Finally, to be able to compare the cooling performance of different materials to a common baseline, it is desirable to test multiple PRC materials at the same time, thus ensuring that the results are obtained under identical environmental conditions. As an example, it could be useful to include a reference PRC material[13,14] or to verify sample reproducibility, substrate and/or size-related effects, and different solar/convection

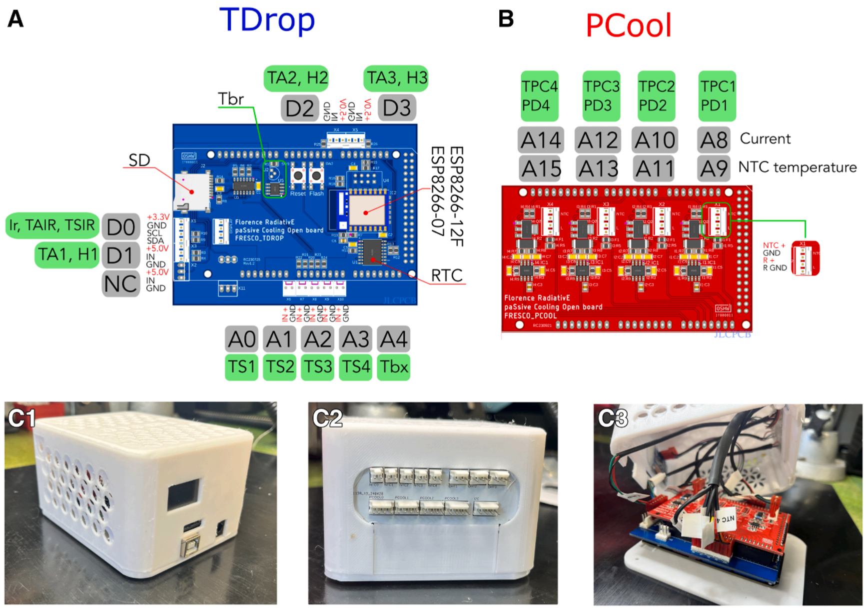



**Figure 1. Assembled PCB with electronic components and enclosure**

(A) PCB for $T_{Drop}$ board.

(B) PCB for $P_{Cool}$ board.

(C.1–C.3) The light gray boxes indicate the I/O pins used on the Arduino MEGA, while the light green boxes indicate the variable name used for the measurements. Different views of the fully assembled FRESCO-board: (C.1) lateral, (C.2) back view of the plug panel, and (C.3) inside with the electronic connection.

shielding configurations, to name a few.[15,16] Moreover, for each tested configuration, at least two specimens are needed at the same time to obtain a more complete overview of their cooling performance by evaluating both the stagnation temperature at zero cooling power and the cooling power at zero temperature difference.[10,17]

Despite the importance of these combined measurements, such comparisons are rarely present in the literature, which involve either just one type of measurement or just one type of sample at a time. To address these needs,[18] we present a fully open-source and open-hardware device offering up to 4 + 4 channels for the testing of different figures of merit of multiple PRC materials. The resulting board is compact, lightweight, and portable; it is easily assembled, starting from low-cost off-the-shelf components (total raw cost of approximately 220 €; see Table S2); and can be conveniently configured through a web application. Embracing an open hardware philosophy is key to fostering innovation and improving this modular device. As such, the project is registered with the Open Source Hardware Association and available on GitHub and Zenodo with the aim of sharing it as an evolving platform open to collaborative development. Adoption of open-hardware solutions has the potential to harmonize the measurement of the main performance indicators of PRC materials, streamlining the simultaneous comparison of multiple materials, the monitoring of multiple parameters related to both external and internal ambient conditions, and the apparent sky temperature.[19]

## RESULTS

### Electronics: Temperature drop and net cooling power modules

The measurement apparatus is driven by a device called FRESCO-board (Florence radiative passive cooling open-board) consisting of a main control unit (Arduino MEGA Rev3 or equivalent) equipped with an ATMEGA 2560 microcontroller. This type of board features 54 digital input/output (I/O) ports, 16 analog signal input ports, 4 universal asynchronous receiver-transmitters (UARTs; hardware serial ports), a 16-MHz crystal oscillator, and an in-circuit serial programming header. The board can be programmed via a Universal Serial Bus (USB) port and powered either through this port or a standard power supply (up to 12 V, 1.2 A). It can be connected to a wall power outlet or an external battery, such as a power bank, for off-grid operation. The MEGA 2560 controller has 512- or 256-kB flash memory, capable of loading large programs. In the current implementation, the microcontroller drives two shields, called temperature drop ($T_{Drop}$) and net cooling power ($P_{Cool}$), which can be stacked onto the main board. The first shield forms the core of the FRESCO-board system, handling temperature and environmental measurements, secure digital (SD) card data storage, and Wi-Fi communication (Figure 1A). An SD card slot is directly connected to the microcontroller's serial peripheral interface, along with a dedicated buffer to log all data streams. This shield also features an RTC (real-time clock) DS2331 to keep track of the date and time. This board is equipped with various output ports, depending on the type of data transmission protocol. The main output ports are A0–4 (5 channels numbered 0–4) for analog signals, and D0–3 for I2C (inter-integrated circuit) communication and digital signals. The first output port D0 uses the I2C protocol to read values from the light meter (BH1750) (converted to W/m$^2$ via a multiplicative factor), a temperature sensor (DS18B20) installed directly on the board, and the IR temperature sensor. The latter (MLX90614) is an IR thermometer for non-contact temperature measurements, equipped with an IR-sensitive thermopile detector chip. Integrated into the MLX90614 are a low noise amplifier, a 17-bit analog-to-digital converter, and a digital signal processor unit returning apparent temperature values with a nominal accuracy of 0.5°C and a resolution of 0.02°C for both sensor ($T_{sen}$) and object ($T_{sky}$) temperature,[20] which are factory calibrated in a wide temperature range from −40°C to +125°C for $T_{sen}$ and from −70°C to +380°C for $T_{sky}$. This sensor is used to obtain a qualitative reading of the apparent sky temperature, which is an important and yet rarely considered factor that is strongly correlated with the radiative cooling performance.[19] Notably, IR sky temperature readings have been shown to

Please cite this article in press as: Werlé et al., Open-hardware platform for synchronous performance testing of multiple passive radiative cooling materials, Cell Reports Physical Science (2025), https://doi.org/10.1016/j.xcrp.2025.102688



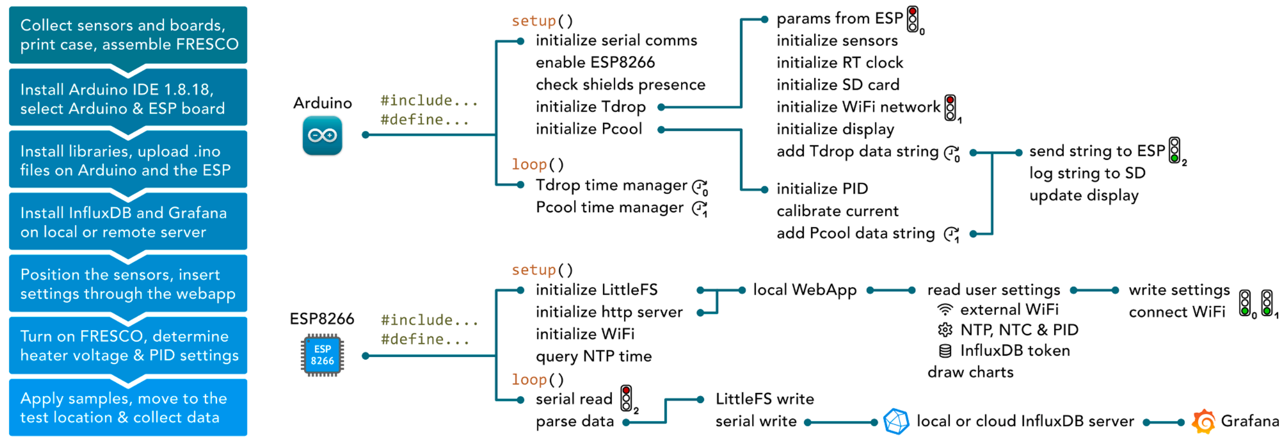



**Figure 2. Block diagram for the deployment of a FRESCO-board**

The Arduino MEGA 2560 code workflow handles the measurement sequence and communication with the ESP using dedicated interrupts (depicted as traffic lights) and two time managers (depicted as clock icons) to ensure that all tasks are performed at the right time. The ESP8266 (both models −12F or −07) firmware workflow shows its initialization and the main loop fetching the data via the serial protocol, which is then transferred via Wi-Fi to the external database and dashboard, and to the web application for live data plotting.

exhibit a very high correlation with the total precipitable water content in the atmospheric column, which is a key parameter determining the instantaneous atmospheric transparency.[21] The sensor is also useful to reveal the passing of clouds during the night, which can help explain abrupt variations in the temperature of PRC samples that are sometimes observed during nighttime hours. The second group of output ports on the $T_{Drop}$ shield is used for analog signals (A0–4). These channels have been used to connect negative temperature coefficient resistors (NTCs) to measure simultaneously up to five temperatures (e.g., four samples plus a point of interest inside the sample-holding platform). Finally, the third group of output ports comprises the digital channels (D1–3) dedicated to DHT22 sensors, which can be used to monitor both air temperature and humidity at three different locations of interest around the measurement setup.

Another main component of the $T_{Drop}$ shield (see Figure 1A) is the ESP8266 board (we tested both the −12F version with integrated antenna and the −07 with the u.fl connector for external and extended antenna). The Wi-Fi module connects to the ATMEGA2560 Serial1 port, enabling it to receive data such as configuration parameters input by the user and send measured data points to a web application or a web server running an InfluxDB instance. InfluxDB can be installed either locally or on a third-party server for real-time data plotting of the data streams. Figures S1–S3 show the complete electronic schematics, and Figure S4 shows the printed circuit board (PCB) layout.

The second module of the FRESCO-board device is the $P_{Cool}$ shield (Figure 1B), offering four channels to simultaneously measure the net cooling power ($P_{Cool}$) of up to four samples. Each output uses one analog channel for the NTCs driving the proportional-integral-derivative (PID) controller and another one to measure voltage to calculate the current passing through a shunt resistor ($R = 1\ \Omega$), and hence the heating power dissipated by the electric heating element. The PCB shown in Figure 1B illustrates the implementation of a PID-controlled temperature management system using the IRLR014NTRPBF metal-oxide-semiconductor field-effect transistor (MOSFET) and the integrated AD820 (or AD8651) operational amplifier. Temperature measurement is achieved using an NTC thermistor, with signal conditioning by the AD820. The PID controller adjusts the gate of the N-channel MOSFET, modulating the power delivered to the heating element through pulse-width modulation. A shunt resistor is used to measure the current through the heating element, with the AD820 amplifying the voltage drop across the shunt for precise current measurement. This setup ensures accurate calculation of power dissipation by combining the voltage across the MOSFET and the current through the shunt resistor. Since the actual amplification gain depends on the real characteristics of the hardware components, it is independently evaluated for each channel at the beginning of every measurement to ensure reproducibility. Filtering components and feedback resistors in the circuit enhance stability and accuracy in temperature regulation, providing a robust solution for precise temperature control and power monitoring. Further details about the $P_{Cool}$ initialization are reported in the methods section, while supplemental figures detail the electronic schematics (Figures S5–S7) and PCB layout (Figure S8).

The FRESCO-board with the $T_{Drop}$ and $P_{Cool}$ modules can be assembled into a compact enclosure, which we realized using a fused deposition modeling (FDM) three-dimensional (3D) printer (Anycubic i3 Mega), based on a 3D drawing, which is available on GitHub (see Figure S9). Figure 1C.1 shows a lateral view of the final device, while Figure 1C.2 displays the back view with the plug panel with labels for all connections. Figure 1C.3 provides a close-up of the internal wire connections within the enclosure. A 3D rendering of the entire device is shown in Video S1.

## Arduino and ESP code workflow

The steps needed to start up the FRESCO-board are summarized in a block diagram in Figure 2. The FRESCO system was developed as an integrated solution for real-time data acquisition, logging, and visualization using Arduino, an organic light-emitting diode display (OLED), and an ESP8266 module connected via serial channels to control external parameters, sharing data through a custom web application, as well as through InfluxDB and Grafana. The implementation followed a structured approach encompassing hardware setup such as collecting all necessary components, including sensors, microcontrollers (Arduino and ESP8266), and peripheral hardware such as SD card modules and communication shields, firmware development, server integration, and data visualization. The firmware-development-required libraries were installed, and dedicated ".ino" scripts were developed for each microcontroller. The Arduino code manages serial communication, enabling the ESP8266 module and handling various subsystems such as sensor calibration, RTC synchronization, SD card logging, and Wi-Fi connectivity. The ESP8266 firmware is designed to handle network communication, providing a local web interface for system configuration via an HTTP server (see methods). It further initializes the Wi-Fi connection, synchronizes time via the network time protocol (NTP), and manages data transmission to an external database for remote storage and analysis. A short guide for these initial steps is summarized in the supplemental methods and in Figures S10–S12.

Once operative, the Arduino microcontroller continuously gathers sensor readings, processes data, and manages time-based control mechanisms. Two time managers (represented by clock icons 0 and 1 in Figure 2) coordinate activities: the first manages primary measurements such as ambient temperature, relative humidity, irradiance levels, and sample and sky temperatures. The second time manager oversees PID control processes, organizing and transmitting data to connected modules, saving them on local storage, and updating the display. Microcontroller initialization is divided into a setup phase and a main loop repeating core tasks. $P_{Cool}$ initialization also includes a calibration step for the current readout. Measured data are processed on the fly (conversion and boxcar averaging over multiple measurements), saved locally on the SD card, and transmitted to the ESP8266 via serial communication to be displayed on the FRESCO web application. Details on data storage protocols and the web application are discussed in the supplemental methods and visible in Figure S13. Furthermore, the ESP8266 handles data transmission to InfluxDB for visualization using Grafana (supplemental methods and Figure S14). Two interrupts coordinate tasks between Arduino and the ESP8266, enabling real-time communication and synchronized data transmission/reception between Arduino and the ESP via a serial port. The high sampling rate set by default on the FRESCO-board (1 s) makes it possible to capture the fast dynamic response of the samples to external factors such as the rapid passage of clouds or morning dew evaporation. Internally, each temperature data point is further averaged over a burst of 100 measurements taken at 10-ms intervals to reduce measurement noise and improve the stability of the PID process.

Finally, after a measurement session, raw data can be downloaded as comma-separated files from the Grafana dashboard or directly in text format from the SD card (see supplemental methods). Dedicated scripts (in Python and MATLAB) for reading, analyzing, and plotting the data are available on the main GitHub repository, as well as for calculating the measurement uncertainty of $T_{Drop}$ and $P_{Cool}$ measurements performed with different types of FRESCO-compatible NTCs (see supplemental methods and Figure S15).

## Outdoor experiments

To demonstrate the capabilities of the FRESCO-board platform, we illustrate its use for testing PRC materials in a typical experimental configuration. As discussed previously, due to the variable insulation and thermal shielding properties of the testing setups realized by different groups, it is crucial to dedicate some of the available FRESCO sensors to the monitoring of environmental conditions and temperatures of the sample-holding platform and its surrounding conditions, rather than just the samples. This can help highlight limitations or biases that may be inadvertently introduced by the experimental configuration used for testing the samples. To this purpose, before performing the measurement, it is important to ensure that all sensors give consistent readings within the tolerances specified by the manufacturers and that the PID is calibrated properly. This can be done via preliminary indoor test measurements (see Figure S16), ideally by comparison with a reference sensor and data logger[22,23] using a dedicated $P_{Cool}$ operation mode (see supplemental methods and Note S1).

For our outdoor experiment, we used an aluminum rack measuring 90 cm in length, 40 cm in width, and 120 cm in height. The rack is divided into two shelves using wooden panels, with the lower section housing the FRESCO-board. This section is protected laterally with 3-cm-thick expanded polystyrene (EPS) lateral walls to avoid direct sunlight illumination of the electronic board, while the other two sides are left semi-open to allow the free passage of ambient air, as shown in Figure 3A (left side). A key element for any PRC testing experiment is the accurate measurement of ambient temperature. For this purpose, the ambient temperature sensor should be placed at an appropriate distance from the ground (at least 1.25 m following recommendations from the World Meteorological Organization) and properly shielded from solar radiation.[24] Figure 3B shows a picture of our setup equipped with a commercial radiation shield (SKU 7714, Davis Instruments, CA, USA) fixed at a height of 1.25 m. The irradiance and sky temperature sensors are placed slightly higher to avoid obstacles or shadowing during the day, while the FRESCO-board is placed underneath the rack shelf. For our illustrative experiment, we prepared a configuration to test the $T_{Drop}$ and $P_{Cool}$ of two samples of different types (specular and diffuse) at the same time.

Figure 3A (right side) illustrates the arrangement of the samples on an EPS pedestal, showing details of the $T_{Drop}$ slot with the NTC sensor and of the $P_{Cool}$ slot, which also includes a heating resistor. Schematic top view, lateral view, and cross-sections corresponding to the colored planes cutting through the EPS pedestal help define the positioning of the samples for $T_{Drop}$ and $P_{Cool}$ measurements (see top view and magnified region a). These views also clarify the placement of the NTC sensors in direct contact with each sample (S#) and under each sample (U.S#) (see projections b-b and c-c), as well as the location of the resistive heater and its associated NTC sensor (see projection d-d). The sample holder

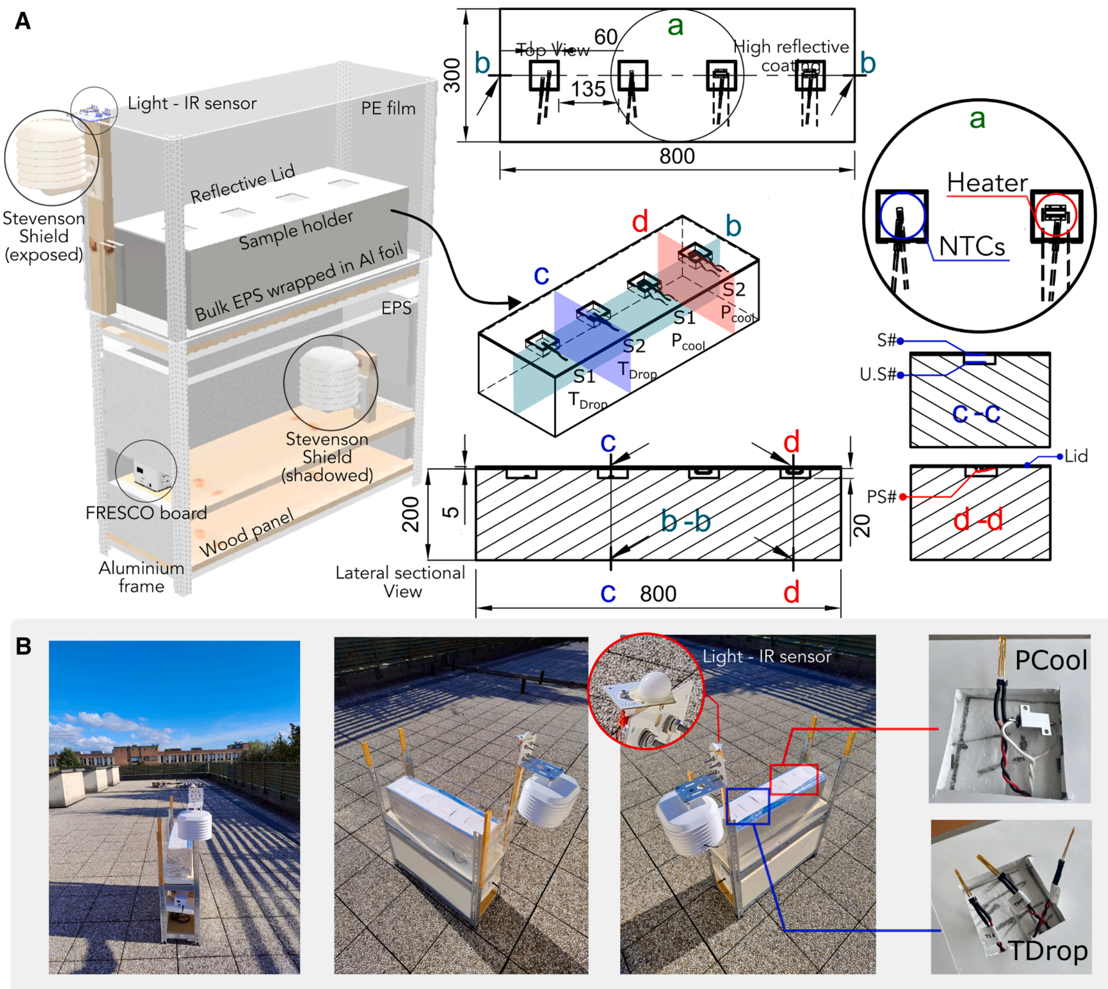



**Figure 3. Experimental setup equipped with FRESCO-board for PRC outdoor measurements**

(A) Schematic view of the apparatus, with a detailed view of the EPS sample holder and the NTCs and heater position.

(B) Photographs of the experimental apparatus highlighting the light and IR sensors, the $T_{Drop}$ and the $P_{Cool}$ slots with a detailed view of the NTCs connections, and the heater resistor used in these configurations.

is made of a 20-cm-high bulk EPS block, providing insulation from the ground and table shelf. The block has a total length of 80 cm, allowing it to accommodate four 6 $\times$ 6-cm slots in a 0.5-cm-thick EPS lid. These slots securely hold equally sized samples, with a small gap underneath to house the NTC sensors and heating elements. The lateral walls of the block are wrapped in low-emissivity aluminum tape to minimize thermal radiation from the ground, while the top surface is entirely covered with a highly reflective solar diffuser film. The same film is also used as one of the tested emitters, which are applied on identical aluminum substrates. Finally, a layer of polyethylene film is wrapped around the vertical posts of the rack to act as a lateral wind barrier (see Figure 3B), with the top left open to allow free air circulation around the samples. This setup prevents overheating of the surrounding environment while promoting natural airflow.

The NTCs used in the experiment (model no. 103JT-025, Semitec, Japan) are 10-kΩ thermistors with a β constant of 3,435 K. Several other NTC models can be alternatively used with FRESCO, some of which have been directly tested in similar experiments as detailed in Table S1. For the $P_{Cool}$ side, a 100-Ω resistive heater (model no. HS25E3 100R F M145, Ohmite, IL, USA) is added to keep the samples at ambient temperature. The contact between the NTC and the sample is ensured using a thermal paste (thermal conductivity >3.5 W/m K) and a layer of adhesive Kapton (3M Polyimide Film Electrical Tape 92) on its back. The heating resistor is directly attached to each sample using a bi-adhesive thermal tape (3M Thermally Conductive Interface Tape 8926). Figure 3B shows the used NTCs and resistive heater and their position with respect to the EPS pedestal. The FRESCO booting loop can be seen in Video S2, after which FRESCO starts performing $T_{Drop}$ and $P_{Cool}$ measurements simultaneously to evaluate the different PRC materials under the same weather conditions.

## PRC outdoor experiments

For our experimental test, we imagine a typical configuration where a material under test is characterized alongside one or

CellPress OPEN ACCESS

Cell Reports Physical Science
Article

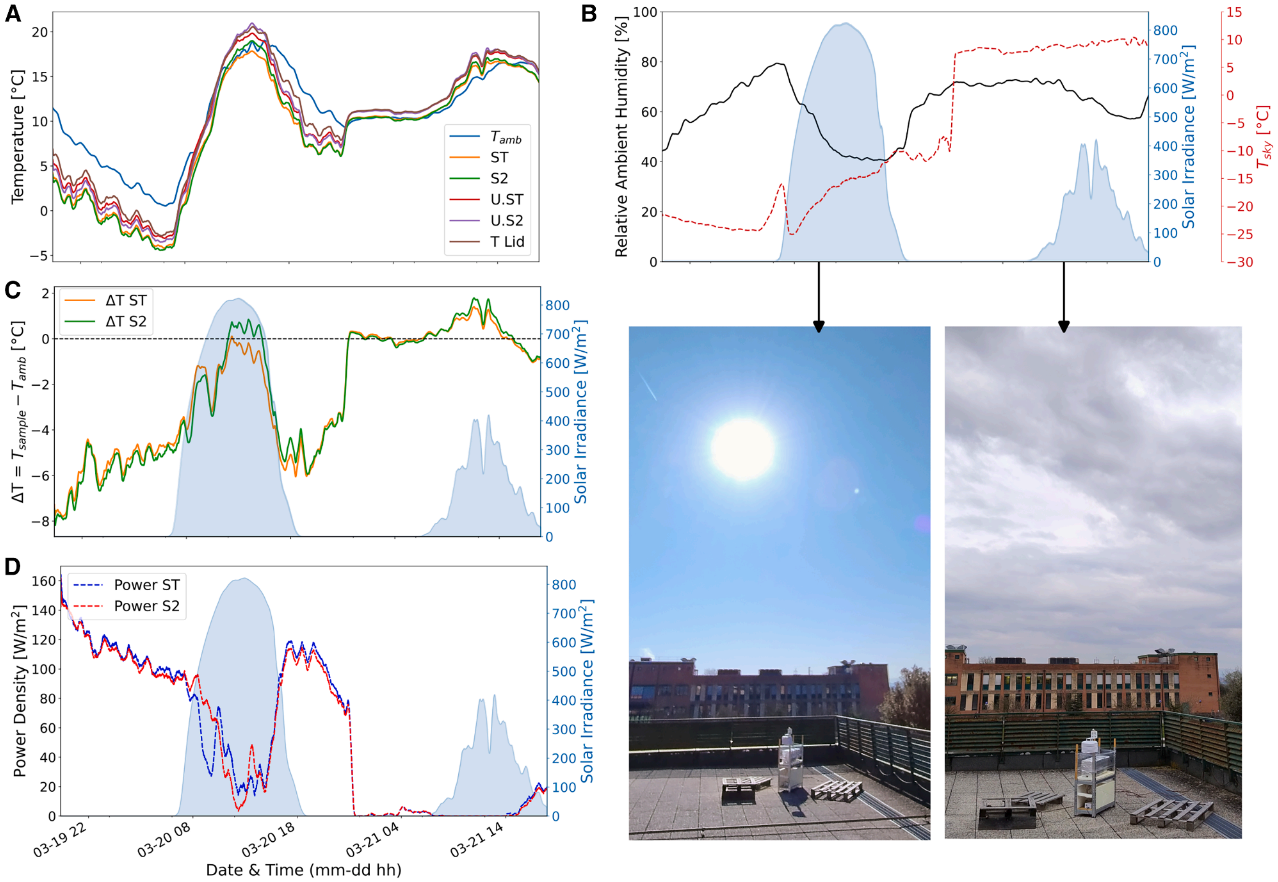



**Figure 4. Outdoor experimental measurements**

(A) Temperature measurements reporting ambient, ST, S2, under both samples, and under the lid.

(B) Relative ambient humidity, solar irradiance, and sky temperature used as a proxy to the presence of clouds, as documented in the photographs taken during the experimental series.

(C) Temperature difference ($\Delta T$) calculated as the difference between samples (ST and S2) and ambient temperatures.

(D) $P_{Cool}$ measured for ST and S2. The second *y* axis reports the solar irradiance as a reference for the daytime and the nighttime. An abrupt interruption in the cooling power exerted by both samples is observed in correspondence with the change in sky conditions.

more reference materials with known properties. Several options have been proposed for this purpose,[14] but we resort for simplicity to a do-it-yourself example reported in the literature, using a specific type of Scotch Tape over a silver reflector.[13] This sample, identified as ST (Scotch Tape), is tested alongside a pre-commercial PRC sample with a white diffuse appearance, identified as S2. Spectral characterization of both samples is presented in Note S2 and Figure S17, according to the relevant standards.[24] Both the Scotch Tape and the pre-commercial film are applied on 6 × 6 × 0.05-cm silvered aluminum reflectors (Almeco VEGA 98) fitting tightly in the sample slots carved into the EPS lid. This silvered substrate is used as the base layer for both samples to ensure that all emitters are applied to equivalent thermal masses and to guarantee homogeneous heat distribution across the sample surface, which is especially relevant for the $P_{Cool}$ measurement. Once the samples were properly positioned, the electronic device was powered on and left to collect data for 2 days between March 19 and 21, 2025, on the rooftop of the LENS Institute near Florence, Italy (43° 49′ 7.9″ N, 11° 11′ 36.8″ E, altitude 50 m).

The experimental results, reported in Figure 4A, show ambient and sample temperatures (ST and S2, under the samples and the lid) data during the experiment. Figure 4B displays ambient humidity (measured inside the Davis Stevenson shield using a DHT22), apparent sky temperature, and solar irradiance. This experimental series is representative of a wide range of ambient temperatures and sky transparency conditions, as documented in the insets of Figure 4B. The abrupt passage from clear to overcast sky conditions is revealed during the night thanks to the sudden increase of the apparent sky temperature and the solar irradiance reduction during the following day. Sky temperature is directly correlated with the downwelling IR irradiance in a wavelength range overlapping with the atmospheric transparency window. Even during apparently clear sky conditions, very different sky temperatures can be recorded, depending on factors such as the presence of high-altitude clouds or humidity or smog that cannot be detected at ground level, showing excellent correlation with the amount of total precipitable water in the atmospheric column.[21] Further tests demonstrating the fast response time and large measurement range of the MLX sensor used for this measurement are presented in Note S3 and Figure S18.

Based on the measured temperatures, Figure 4C displays the temperature difference ($\Delta T$) between the two sample temperatures and ambient temperature. Temperature differences relative to the air pockets below the samples are further shown in Figure S19A (see Note S4). Figure 4D shows the cooling power of the two samples estimated during the same period using the $P_{Cool}$ module, measured as the instantaneous power required to keep the emitter at ambient temperature under the assumption that all heat is dissipated radiatively toward the emitter surface. A $P_{Cool}$ is measured as expected when the samples go below ambient temperature, reaching cooling powers up to 110 W/m$^2$ during the periods of lower solar irradiation, which is consistent with values typically reported in the literature.[11,16,25–28] Figure S19B displays the temperatures measured in contact with the two temperature-controlled samples for the $P_{Cool}$ measurement, showing the effectiveness of the PID feedback in ensuring that they do not fall below the target set point of ambient temperature $T_{amb}$. Additional measurements are shown in Note S5 (Figures S20 and S21), featuring longer measurement sessions during summer conditions with similar qualitative results, which confirms the ability of the FRESCO-board system to collect and transmit data across several days unattended.

## DISCUSSION

FRESCO-board is a modular, open-hardware platform developed for comprehensive monitoring and data logging in experiments evaluating the cooling performance of PRC materials. As such, it can fill the current literature gap regarding reproducible strategies for in-field cooling performance assessment and comparison among different PRC materials. In addition to the inherent challenges connected to testing PRC materials outdoors, biases and "manipulated conditions" have also been reported in the literature[10,17,24,29] (e.g., related to the selection of particularly favorable experimental locations, artificial suppression of convective heat exchange, or inappropriate choice of ambient temperature references). Informed by these shortcomings, FRESCO-board is designed to monitor multiple reference temperatures at once, both inside and around the insulated sample holders, thus facilitating the comparison and identification of inappropriate sensor positioning or shielding of the reference temperature sensor. Additionally, we conducted our experiment in a typical application environment at low altitude, without suppressing natural convection.

Another relevant design principle that guided the development of FRESCO is related to its ability to collect the instantaneous temperature and cooling power for the same sample under the same environmental conditions. Previous works highlighted the importance of such combined measurement, which provides both a more comprehensive picture of the overall cooling potential of a PRC material and extremely robust information on the non-radiative heat exchange contributions at play during the measurement.[10]

Thanks to its compact design and versatile operation, FRESCO-board provides a practical and cost-effective solution for standardizing in-field data collection in PRC research. Its multi-channel capability enables testing of different materials or configurations in parallel, capturing both $T_{Drop}$ and $P_{Cool}$ power simultaneously. This approach enhances the reliability and comparability of results, addressing a common limitation in previous experimental setups that could record only one type of data at a time. The total cost of the proposed system is approximately 220€, making it an accessible solution for research groups worldwide (complete bill of materials provided in Table S2). Pick-and-place files and documentation are available in the GitHub repository, enabling fast, low-cost prototyping using standard PCB manufacturing services.

Because of its collaborative development and open-source code base, we envision continuing to improve the FRESCO-board and overcome some of its current limitations—for example, the typical power supply of Arduino MEGA limits the maximum power that can be dissipated by the resistive heating elements. Assuming a conservative maximum target of 170 W/m$^2$ dissipated by each sample, this currently limits the maximum sample size to about 8 $\times$ 8 cm. Future implementations could consider more recent Arduino platforms such as the GIGA R1, which can run on a more powerful power supply (maximum 24 V), and would additionally include all current functionalities (including Wi-Fi connection and an integrated RTC) in a single board. When testing samples across extreme temperature ranges, the accuracy of NTC measurements can be improved further by deriving Steinhart-Hart parameters replacing the current beta law, which is currently under development in the FRESCO repository. Additionally, at present, FRESCO does not include a wind speed sensor. However, several Arduino-compatible options are readily available and could be integrated in future versions. Similarly, the addition of an atmospheric pressure sensor would provide another relevant yet rarely considered data stream, given its link to weather patterns and precipitable water content. Finally, the inclusion of a dedicated UV sensor could enable real-time tracking of UV irradiance, which may be relevant for evaluating the performance of PRC coatings with varying UV reflectance properties.

All in all, this work shows that comprehensive experimental studies of the PRC effects can be affordable and deployed easily, providing inspiration on how to improve the robustness of these measurements and shifting the attention from the continuous development of new PRC materials to their comparable and synchronous testing under identical ambient conditions.

## METHODS

### Firmware upload

To set up both the Arduino and ESP8266 microcontrollers, it is recommended to use Arduino IDE version 1.8.18 for compatibility with all hardware and software libraries, which is available from the official Arduino website. After selecting the correct board in the IDE, the tested Arduino sketch can be uploaded to compatible boards. For the ESP8266, users should wire the USB-UART to the microcontroller (see supplemental methods and Figure S10) and follow the specific booting sequence to enter program mode and upload the firmware (see supplemental methods). Additionally, a plotting package is required for the web application homepage to display correctly, with further instructions and all necessary files available in the official GitHub repository. Further details are provided in the supplemental methods.

## FRESCO-board initialization

Prior to setting up the experiment, NTC sensors should be characterized in a controlled environment to verify their compliance with the manufacturer's technical specifications, as discussed in Note S1. When compared among themselves or to a reference sensor, small systematic deviations are typically observed, with some sensors displaying slightly higher and others slightly lower readings. To adopt a conservative approach and minimize the risk of overestimating the cooling performance of a passive daytime radiative cooling coating, we recommend using slightly "hot" sensors for sample measurements and slightly "cold" sensors for ambient temperature monitoring.

When mounting the NTC sensors and electric heaters, care should be taken to ensure good thermal contact with the sample substrates. This can be done by attaching the sensors to the metal with Kapton tape to further shield the sensors from ambient temperature fluctuations. Thermal paste should be applied sparingly or be replaced with thin thermal double tape to ensure that the adhesion between the substrate and the Kapton tape is not weakened.

## FRESCO-board PID settings

Once the heating elements are mounted on the $P_{Cool}$ channels, their voltage drop should be measured and stored in the relative PSUPPLY_VOLTAGE variable in the Arduino firmware. With a 12-V external power supply, typically around 10.8 V are available at the heating resistors accounting for the voltage drops introduced by the MOSFET and internal diodes. Once this value is set, PID parameters can be tuned during a laboratory test session by setting a constant target temperature above ambient conditions and tracking the system time response. To this end, FRESCO-board allows setting the PID target temperature to track the reading of another sensor (by default, the sensor tracking ambient temperature), or to a constant user-defined temperature (see supplemental methods).

For our system, we determined values of 225, 0.75, and 10 for the PID parameters, respectively. These parameters are specific to the experimental configuration and may vary depending on the sample size and substrate material used. For tuning the PID parameters, the closed-loop Takahashi method is recommended.[30]

## NTP synchronization

As a backup storage when a Wi-Fi network is not unreliable or not available, FRESCO-board stores recorded data locally on an SD card. To ensure logging with the correct time stamp, the board can be connected just for a few seconds to a hotspot and then rebooted to allow it to sync with one of the available NTP servers (see supplemental methods).

## RESOURCE AVAILABILITY

### Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact Diederik S. Wiersma (diederik.wiersma@unifi.it).

### Materials availability

This study did not generate new unique materials.

### Data and code availability

- The data supporting the findings of this study are available within the paper and at Zenodo: https://doi.org/10.5281/zenodo.13919077.
- The firmware used for Arduino microcontroller (ATMEGA 2560) and ESP8266 control and communication are available at GitHub: https://github.com/GiuseppeELio/FRESCO-Board or at Zenodo: https://doi.org/10.5281/zenodo.13919077.

## ACKNOWLEDGMENTS

The authors thank CoolingPhotonics Company (Barcelona, Spain) for the economic support offered through the technological transfer agreement framework called "FRESCO - Data Logger" and the Sustainable Energy, Machinery and Buildings (SEMB) group at the Universitat de Lleida for their support with samples. Part of this work is supported by the European project PaRaMetriC, code 21GRD03. The project 21GRD03 PaRaMetriC received funding from the European Partnership on Metrology, co-financed by the European Union's Horizon Europe Research and Innovation Programme, and from the Participating States. G.E.L. acknowledges support from the FSE-REACT EU program financed by National Social Fund - National Operative Research Program and Innovation 2014–2020 (D.M. 1062/2021), personal grant no. 10-G-15049-2. J.W. acknowledges co-funding by the European Union - PON Research and Innovation 2014–2020, in accordance with Article 24, paragraph 3a, of law no. 240 of December 30, 2010, as amended, and Ministerial Decree No. 1061 of August 10, 2021.

## AUTHOR CONTRIBUTIONS

G.E.L. conceived the FRESCO-board and worked on its hardware and software implementation. R.C. revised the design of the electronic boards. J.W. realized the outdoor experimental apparatus and contributed to the software and hardware development. G.E.L., J.W., and L.P. performed the outdoor measurements and collected the PRC materials used in the experiment. E.P. designed and realized the FDM case. G.E.L. prepared the manuscript, with input from all authors. D.S.W., L.P., and G.E.L. supervised the research project.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

## SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.xcrp.2025.102688.

Received: December 18, 2024
Revised: April 29, 2025
Accepted: June 10, 2025

## REFERENCES

1. Li, C., Zhang, H., and Wang, J. (2023). Facilitating sustainable greenhouse production with radiative cooling. Device *1*, 100114. https://doi.org/10.1016/j.device.2023.100114.

2. Raman, A.P., Anoma, M.A., Zhu, L., Rephaeli, E., and Fan, S. (2014). Passive radiative cooling below ambient air temperature under direct sunlight. Nature *515*, 540–544. https://doi.org/10.1038/nature13883.
3. So, S., Yun, J., Ko, B., Lee, D., Kim, M., Noh, J., Park, C., Park, J., and Rho, J. (2024). Radiative Cooling for Energy Sustainability: From Fundamentals to Fabrication Methods Toward Commercialization. Adv. Sci. *11*, 2305067. https://doi.org/10.1002/advs.202305067.
4. Liu, S., Zhang, F., Chen, X., Yan, H., Chen, W., and Chen, M. (2024). Thin paints for durable and scalable radiative cooling. J. Energy Chem. *90*, 176–182. https://doi.org/10.1016/j.jechem.2023.11.016.
5. Chae, D., Son, S., Liu, Y., Lim, H., and Lee, H. (2020). High-Performance Daytime Radiative Cooler and Near-Ideal Selective Emitter Enabled by Transparent Sapphire Substrate. Adv. Sci. *7*, 2001577. https://doi.org/10.1002/advs.202001577.
6. Song, X., Gao, Y., Farooq, A.S., and Zhang, P. (2021). Temperature non-uniformity in the radiative cooler and its effect on performance under various humidity conditions. Sol. Energy *220*, 498–508. https://doi.org/10.1016/j.solener.2021.03.064.
7. Song, Y., Zhan, Y., Li, Y., and Li, J. (2023). Scalable fabrication of super-elastic TPU membrane with hierarchical pores for subambient daytime radiative cooling. Sol. Energy *256*, 151–157. https://doi.org/10.1016/j.solener.2023.03.018.
8. Li, X., Ding, Z., Lio, G.E., Zhao, J., Xu, H., Pattelli, L., Pan, L., and Li, Y. (2023). Strain-adjustable reflectivity of polyurethane nanofiber membrane for thermal management applications. Chem. Eng. J. *461*, 142095. https://doi.org/10.1016/j.cej.2023.142095.
9. Song, Q., Tran, T., Herrmann, K., Lauster, T., Breitenbach, M., and Retsch, M. (2022). A tailored indoor setup for reproducible passive daytime cooling characterization. Cell Rep. Phys. Sci. *3*, 100986. https://doi.org/10.1016/j.xcrp.2022.100986.
10. Fan, F., Xu, D., Zhu, Y., Tan, G., and Zhao, D. (2023). A simple, accurate, and universal method for characterizing and comparing radiative cooling materials and devices. Int. J. Heat Mass Tran. *200*, 123494. https://doi.org/10.1016/j.ijheatmasstransfer.2022.123494.
11. Lio, G.E., Werlé, J., Arduini, M., Wiersma, D.S., Manara, J., and Pattelli, L. (2024). Radiative Cooling Potential of a Water-Based Paint Formulation under Realistic Application Conditions. ACS Appl. Opt. Mater. *2*, 2459–2468. https://doi.org/10.1021/acsaom.4c00099.
12. Felicelli, A., Katsamba, I., Barrios, F., Zhang, Y., Guo, Z., Peoples, J., Chiu, G., and Ruan, X. (2022). Thin layer lightweight and ultrawhite hexagonal boron nitride nanoporous paints for daytime radiative cooling. Cell Rep. Phys. Sci. *3*, 101058. https://doi.org/10.1016/j.xcrp.2022.101058.
13. Huang, X., Mandal, J., and Raman, A.P. (2021). Do-it-yourself radiative cooler as a radiative cooling standard and cooling component for device design. J. Photon. Energy *12*, 012112. https://doi.org/10.1117/1.JPE.12.012112.
14. Adibekyan, A., Schumacher, J., Pattelli, L., Manara, J., Meriç, S., Bazkir, Ö., Cucchi, C., Sprengard, C., Pérez, G., Campos, J., et al. (2025). Emissivity and Reflectivity Measurements for Passive Radiative Cooling Technologies. Int. J. Thermophys. *46*, 66. https://doi.org/10.1007/s10765-025-03532-6.
15. Zhou, L., Yin, X., and Gan, Q. (2023). Best practices for radiative cooling. Nat. Sustain. *6*, 1030–1032. https://doi.org/10.1038/s41893-023-01170-0.
16. Lio, G.E., Levorin, S., Erdoğan, A., Werlé, J., Corso, A.J., Schenato, L., Wiersma, D.S., Santagiustina, M., Pattelli, L., and Pelizzo, M.G. (2024). Nanoporous Film Layers to Enhance the Performance of Passive Radiative Cooling Paint Mixtures. Int. J. Thermophys. *45*, 153. https://doi.org/10.1007/s10765-024-03439-8.
17. Sui, C., and Hsu, P.-C. (2024). Standardizing the Thermodynamic Definition of Daytime Subambient Radiative Cooling. ACS Energy Lett. *9*, 2997–3000. https://doi.org/10.1021/acsenergylett.4c00909.
18. Yoon, S., Chae, D., Seo, J., Choi, M., Lim, H., Lee, H., and Lee, B.J. (2022). Development of a device for characterizing radiative cooling performance. Appl. Therm. Eng. *213*, 118744. https://doi.org/10.1016/j.applthermaleng.2022.118744.
19. Wong, R.Y.M., Tso, C.Y., Jeong, S.Y., Fu, S.C., and Chao, C.Y.H. (2023). Critical sky temperatures for passive radiative cooling. Renew. Energy *211*, 214–226. https://doi.org/10.1016/j.renene.2023.04.142.
20. Wang, X., Yang, Y., Zhang, Z., Luo, Y., and Li, Z. (2021). Design of Temperature Measurement Identification Instrument based on OpenMV and MLX90614. In 2021 IEEE International Conference on Mechatronics and Automation (ICMA) (IEEE), pp. 1407–1412. https://doi.org/10.1109/ICMA52036.2021.9512718.
21. Mims, F.M., Chambers, L.H., and Brooks, D.R. (2011). Measuring Total Column Water Vapor by Pointing an Infrared Thermometer at the Sky. Bull. Am. Meteorol. Soc. *92*, 1311–1320. https://doi.org/10.1175/2011BAMS3215.1.
22. Muselli, M. (2010). Passive cooling for air-conditioning energy savings with new radiative low-cost coatings. Energy Build. *42*, 945–954. https://doi.org/10.1016/j.enbuild.2010.01.006.
23. Gao, M., Han, X., Chen, F., Zhou, W., Liu, P., Shan, Y., Chen, Y., Li, J., Zhang, R., Wang, S., et al. (2019). Approach to fabricating high-performance cooler with near-ideal emissive spectrum for above-ambient air temperature radiative cooling. Sol. Energy Mater. Sol. Cell. *200*, 110013. https://doi.org/10.1016/j.solmat.2019.110013.
24. Bu, K., Huang, X., Li, X., and Bao, H. (2023). Consistent Assessment of the Cooling Performance of Radiative Cooling Materials. Adv. Funct. Mater. *33*, 2307191. https://doi.org/10.1002/adfm.202307191.
25. Jeong, S.Y., Tso, C.Y., Wong, Y.M., Chao, C.Y.H., and Huang, B. (2020). Daytime passive radiative cooling by ultra emissive bio-inspired polymeric surface. Sol. Energy Mater. Sol. Cell. *206*, 110296. https://doi.org/10.1016/j.solmat.2019.110296.
26. Li, X., Peoples, J., Huang, Z., Zhao, Z., Qiu, J., and Ruan, X. (2020). Full Daytime Sub-ambient Radiative Cooling in Commercial-like Paints with High Figure of Merit. Cell Rep. Phys. Sci. *1*, 100221. https://doi.org/10.17632/GVXXR8J62W.1.
27. Wang, T., Wu, Y., Shi, L., Hu, X., Chen, M., and Wu, L. (2021). A structural polymer for highly efficient all-day passive radiative cooling. Nat. Commun. *12*, 365. https://doi.org/10.1038/s41467-020-20646-7.
28. Zhou, L., Song, H., Zhang, N., Rada, J., Singer, M., Zhang, H., Ooi, B.S., Yu, Z., and Gan, Q. (2021). Hybrid concentrated radiative cooling and solar heating in a single system. Cell Rep. Phys. Sci. *2*, 100338. https://doi.org/10.1016/j.xcrp.2021.100338.
29. Feng, C., Lei, Y., Huang, X., Zhang, W., Feng, Y., and Zheng, X. (2022). Experimental and theoretical analysis of sub-ambient cooling with long-wave radiative coating. Renew. Energy *193*, 634–644. https://doi.org/10.1016/j.renene.2022.05.037.
30. Takahashi, E., and Kaneko, O. (2019). A New Approach to Prediction of Responses in Closed Loop Systems Based on the Direct Usage of One-shot Experimental Data. Transaction. of SICE. *55*, 324–330. https://doi.org/10.9746/sicetr.55.324.