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Development of a solar hybrid air conditioner

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ABSTRACT

This research presents the development of a solar hybrid air conditioner. The primary aim was to develop an air-conditioning system that would be suitable and affordable for consumers and to reduce the amount of carbon dioxide released into the atmosphere from fossil fuel consumption. Calculated convective heat Coefficients (h) obtained was used to analyze the performance of the machine. Cooling time was obtained by using the stopwatch. The result obtained showed that the initial surface temperature of the sample room varies from 28^{o}C to 32^{o}C. While an average instantaneous solar fraction of 45 percent, 60 percent and 40 percent are attained within the time frames of 0–120 minutes (that is, 9:00 am–11:00 am); 120–400 minutes (9:01 am–4:00 pm); and 400–550 minutes (4:01 pm–5:30:00 pm). For the air conditioner with a nominal cooling capacity of 2.5 kW and maximum power usage of roughly 1.19 kW, a solar PV system with 1219489.32 Wp, 24 V battery setup has a monthly mean solar fraction of 71%. The 1040 Wp solar PV system generates roughly 1211 kWh of electricity per year, according to calculations.

Keywords: Solar hybrid air conditioner, convective heat Coefficients, performance, cooling time

1. INTRODUCTION

In recent years, the global consumption of energy is increasing at an alarming rate. This has already sparked concerns about possible supply problems, energy resource depletion and worsening environmental consequences. Building energy use is on the rise across the world. The cost of living, both residential and commercial, has gradually increased. In wealthy countries, the percentages increment ranges from 20% to 40% (Koroneos et al., 2009; Chua et al., 2013). If global warming projections are right, the situation is deteriorating day by day. As a result, finding new ways to preserve and better the indoor environment quality while meeting possibly more stringent performance criteria is critical and doing so without harming the environment is critical (Khan and Arsalan, 2016; Enongene et al., 2019). Solar collectors, a storage tank, a control unit, pipelines and pumps, as well as a thermally driven cooling machine, make up a typical solar thermal system. Solar heat is utilized to power thermally driven cooling machinery like absorption chillers and desiccant cooling systems in solar cooling systems (Saudagar et al., 2013; Yang et al., 2008).

The use of solar energy for cooling in most structures is an appealing concept because the cooling load corresponds to solar energy availability in most cases and so the cooling requirements of a building are nearly in phase with sun incidence. Solar cooling systems offer the benefit of using environmentally friendly operating fluids like water or salt solutions. They are environmentally friendly and energy-efficient. They can be utilized to improve the indoor air quality of all types of buildings as stand-alone systems or in conjunction with traditional air conditioning (Abu-Zour and Riffat, 2007; Ha and Vakiloroaya, 2012). The major objective is to reduce energy usage and CO_2 emissions by utilizing "zero-emission" technologies. Current energy supply and consumption patterns are unsustainable, both economically and environmentally. It is desirable to alter our current course, but doing so will necessitate an energy revolution, with low-carbon energy technology playing a critical role. If we are to meet our green-house gas (GHG) emission targets, we will need to implement energy efficiency, a variety of renewable energy sources, carbon capture and storage (CCS), nuclear power and new transportation technologies (Ismail et al., 2012; Opokua et al., 2018).

In the impending energy revolution, solar heating and cooling will play a significant role. Solar PV cooling technology, solar thermoelectrical cooling, solar thermo-mechanical cooling and solar thermal cooling are the four cooling techniques available. The first is a photovoltaic (PV) solar energy system, in which solar energy is turned into electrical energy and used for refrigeration in the same way traditional methods are employed. The thermoelectric techniques are used in the second one to create cool. The third transforms thermal energy into mechanical energy, which is used to create the cooling effect. A solar thermal refrigeration system is used as the fourth method. Heating and cooling (49%) have greater ultimate energy consumption in Europe than electricity (20%) or transportation (31%), according to Naskar et al., (2018).

In hot and humid countries, the ambient temperature and relative humidity can reach 41°C and 84 percent, respectively. As a result, methods and techniques for artificially improving outdoor thermal comfort have been intensively researched. Indoor temperatures should be kept between 20-25 °C and 50 to 55 percent relative humidity, according to the ANSI, (2013) and ISO 7730, (2005) standards, as well as other published research studies on indoor thermal comfort for people. In hot and humid areas, room air-conditioning is consequently critical for providing the essential interior thermal comfort for typical human activities and productive office work (Njoku, 2013; Okoye et al., 2016; Akusu et al., 2018). In both developed and developing countries, air-conditioning equipment can account for 50–80 percent of total electricity usage in buildings.

Because of substantial transmission and distribution losses in developing countries like Nigeria, the cost of electricity from conventional fossil-fuel power plants continues to rise. Therefore, this project aims to develop a solar hybrid air-conditioning, to serve as an alternative means to achieving cold air with less consumption of energy. It is renewable, with reduced amount of energy consumed by traditional air conditioning units, so increasing efficiency, boosting the economy, lowering costs, reducing pollution and conserving energy.

2. MATERIALS AND METHODS

The following properties were considered in the selection of the material used for the construction of the solar hybrid air conditioner:

i. Mechanical properties such as strength, wear resistance, hardness, fatigue, etc.

ii. Physical properties like shape, size, density, freezing point, condensing pressure, evaporating pressure, etc.

iii. Chemical properties like flammability, toxicity, the heat of combustion, chemical stability, acidity, etc.

iv. Availability of materials: The materials used were based on their availability in the material without any stress of looking for it.

v. Cost of materials: The materials which were used are less expensive and are available even for purchase.

vi. Strength of the materials: The strength of the materials used was determined by using data and formulas to avoid failure.

vii. Environmental and safety properties: Refrigerants with minimal global warming potentials will aid in minimizing the problem of global warming.

System Operating Principle

The component parts which were locally sourced for this study comprises of a compressor, a condenser, an expansion device, an evaporator, a solar panel, an inverter and a battery make up a single-stage vapor-compression solar air conditioner. A schematic block diagram of the novel hybrid solar air conditioning system is shown (Figure 1). A mixture of liquid and vapor refrigerant enters the evaporator to begin the cycle (point 1). An evaporator coil absorbs the heat from heated air. The refrigerant condition changes from liquid to gas throughout this process and it becomes superheated near the evaporator exit. The super-heated vapor then enters the compressor (point 2), where the temperature rises as the pressure rise. After the compressor, a vacuum solar panel uses sun radiation as a heat source to preheat the water. As a result, the vacuum solar collector reheats the refrigerant to meet the requisite superheat temperature, lowering the compressor's required electrical energy.

However, even with partial load, this design has the disadvantage of increasing the refrigerant temperature entering the condenser. The fact that the condensing temperature varies due to variations in the ambient temperature accounts for this. As a result, during partial loads, the required refrigerant temperature entering the condenser is lower than at full loads. In this work, a unique design for increasing the refrigerant sub-cool temperature is incorporated into the system. After the compressor, a one-way proportional control valve is fitted to adjust the refrigerant mass flow rate. As a result, the temperature of the refrigerant entering the condenser can be adjusted using the control valve. The refrigerant superheat temperature exiting the compressor is generally sufficient for condenser heat rejection under partial loads, when the condensing temperature is low and so the control valve shall direct the refrigerant to proceed directly through the new by-pass discharge line.

The refrigerant from the compressor passes through the copper coil within the tank where the heat exchange takes place during a high cooling demand when the condensing temperature is high (point 3). The control valve should function continually to keep the desired temperature entering the condenser because the nature of building cooling loads and ambient conditions is highly transient. The high-pressure superheated gas proceeds to the condenser for heat rejection of the ambient air after passing through the control valve (point 4). The refrigerant temperature is reduced further in the condenser, causing it to de-superheat and the refrigerant liquid is therefore sub-cooled as it enters the expansion device. The expansion device (point 5) reduces the pressure and temperature of the high-pressure sub-cooled refrigerant while also controlling the flow rate of the refrigerant entering the evaporator.

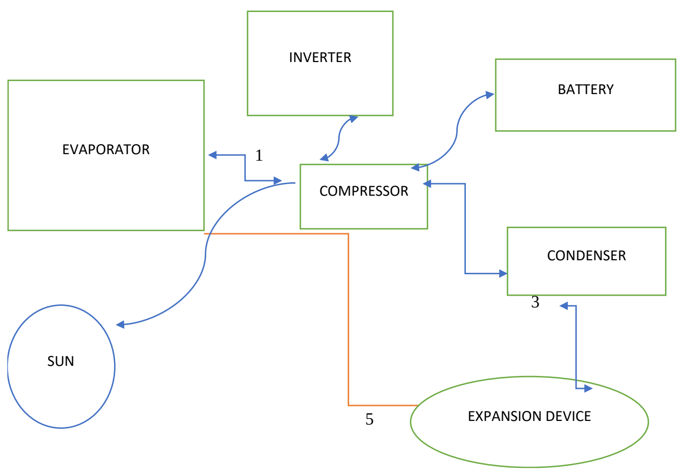
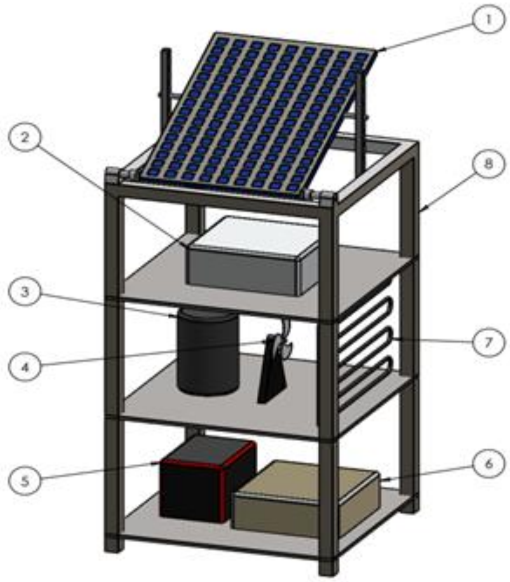


Figure 1 Block diagram of the novel hybrid solar air conditioning system

Experimental setup

The research was carried out with the help of an experimental solar hybrid air conditioner. The experimental set-up consists primarily of two parts: An air-conditioned chamber served by the evaporator unit and a condensing unit with a solar vacuum collector. The chosen air-conditioned room has a floor space of 2 square meters and a height of 0.1 meters. The air conditioner has a nominal cooling capacity of 6 kW. The facility employs the refrigerant R134A as a working fluid and features one scroll hermetic compressor. There is 1.8 kg of charged refrigerant in the system. The plant condenser is an air-cooled shell with a coated fin-tube design. The solar panel is set up and built to allow for a variety of testing under various operating circumstances. All operating variables are measured using high-precision sensors/transducers. Meteorological parameters (global solar radiation, ambient temperature and ambient relative humidity), indoor temperature and relative humidity, refrigerant temperature before and after the solar storage tank and after the condenser and evaporator, as well as the plant total power consumption are all measured. The system set-up plant is shown on the schematic diagram (Figure 2).



S/No	ITEM NUMBER	ITEM NAME
1	1	Solar Panel
2	2	Evaporator
3	3	Compressor
4	4	Fan
5	5	Battery
6	6	Inverter
7	7	Condeser
8	8	Frame Stand

Figure 2 Schematics of a solar hybrid air conditioner

The air-conditioner was set to 20 degrees Celsius for the trial. The following measurements were made at the same time:
Air conditioner power consumption,
Solar PV array power output,
Grid power supply and
Battery voltage

Throughout 3 months/cycles (January 2022–March 2022), 90 days of data were gathered from dawn to dusk. This work intends to evaluate how much solar PV system energy contributes to the entire energy demand of an air conditioner for cooling an office during a typical working day from sunrise to sunset.

Table 1 Size of system components

Component	Size
Solar panels	1040 Wp
Inverter	2.0 kVA
Battery	24 V system, deep cycle
Utility grid	50 Hz

Table 2 Specifications of solar PV module

Maximum power	240 V
Maximum power voltage	240 V
Maximum power current	8.44 A
Open circuit voltage	38.6 V
Short circuit current	9.03 A
Nominal operating cells' temperature	45 ± 2 °C
Maximum system voltage	1000 VDC

Table 3 Specifications of the hybrid inverter

Technology	Pure sine wave with integrated PWM charge controller
Brand	Opti-Solar (SP2000 Efecto)
Rated power	2000 VA/1600 Watt
No-load power consumption	Less than 20 Watt (< 20 W)
DC input	24 VDC, 66.6 A
AC input	240 Volt, 50 Hz, 13.4 A, 1ϕ

DC output	27 VDC, 30/20 A
AC output	230 Volts ± 5%, 50 Hz, 8.7 A, 1ϕ
Solar charger	Mode 50 A-rated current, 24 VDC system voltage, 30–32 VDC operating voltage range, 60 VDC max. solar voltage

Experimental Design

The experimental design was done using (eq.1) as:

$$n_i \times m_i = E_T \quad (1)$$

Where,

n_i = The number of experiments per fluid

m_i = The number of processes

E_T = The total experiments.

Since the degree of freedom is 10, subsequent upon 6 variant fluids, 60 experiments were done.

Design Procedure

The design analysis and the construction of a solar hybrid air conditioner were done at Department of Mechanical Engineering, Abia State University, Uturu. This is based on various diameters D, of 0.10mm, 0.15mm 0.30mm, 0.35mm and 0.40mm with corresponding various varying gaps H, of 0.115, 0.125, 0.135, 0.145 and 0.155mm for top surface conventional process and diameters D, of 0.10, 0.15, 0.30, 0.35 and 0.40mm with corresponding gaps of 0.55mm, 0.65mm, 0.75mm, 0.85mm and 0.95mm for the bottom surface process at five different cooling controlled temperatures of 22°C, 24°C, 26°C,30°C and 32°C respectively of the heat exchangers for both processes. These values of room temperature (t) obtained represent various cooling flow rates at various constant diameters. Thereafter, calculated convective heat Coefficients (h) obtained was used to analyze the performance of the machine. Cooling time was obtained by using the stopwatch. The initial surface temperature of the sample room varies from 28°C to 32°C. Experiments were carried out with the following varying parameters –low and high pressures, initial and final temperatures. Readings were as well obtained from the four thermocouples T_1, T_2, T_3, T_4 after we had monitored them until the nearly steady-state isothermal condition for refrigeration and air conditioning training equipment in Thermofluid Laboratory, Abia State University Uturu, Nigeria. The solar PV array energy generation was calculated using the Eq. 2 panel, the solar cell technology and the charge controller's power electronics.

$$E_{PV} = \sum_0^T I_{DC} x V_{DC} x \Delta t \quad (2)$$

Where,

T = The analysis period in a day (from sunrise to sunset).

A= Fluke 345 power quality clamp meter was used to measure the solar PV array's instantaneous DC (I_{DC}) and voltage (V_{DC}). The current and voltage accuracies of the power quality clamp meter are 1.5 percent and 1.0 percent, respectively.

The air conditioner instantaneous power consumption was tracked. Maximum power consumption ($P_{c,max}$) data on the air conditioner was utilized to determine the size of the inverter (C_{inv}) Eq (3).

$$C_{inv} = \frac{P_{c,max}}{P.F x \eta_{inv}} \quad (3)$$

Where,

$P.F$ = The load device power factor

inv = The inverter efficiency.

The variable speed air conditioner power factor was determined at $P.F$ = 0.97 by the Fluke 345 power quality tester. The manufacturer claims that the inverter efficiency is 90%.

The battery depth of discharge (DoD) was kept below 60% during the system's operation to ensure long battery life as shown in eq (4).

$$C_{batt} = \frac{E_{daily} x D_o A}{V_{batt} x EFF_{batt} x D_o A} \quad (4)$$

Where,

E_{daily} = The average daily energy consumption; $D_o A$ = The days of autonomy; V_{batt} = The battery system voltage; EFF_{batt}= The efficiency of the battery.

$$\text{Battery Capacity (Ah)} = \frac{\text{Total Watt−hours per day used by the appliance}}{(0.85 \text{ x } 0.6 \text{ x nominal battery voltage})} \text{x Days of autonom} \quad (5)$$

Space Cooling Load Calculation of Solar Hybrid Air Conditioning

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) handbook guideline for cooling load estimation, which has been used around the world by engineers, was adopted. The cooling load temperature difference/cooling load factor calculation depends on the right information and interpretation of the available data

The total cooling load of a building has to do with both the external and internal loads. The external load has to do with the transfer of conduction through the wall of the building, roof floor, door, etc with the transfer of heat by radiation.

a.) Load through the Roof and Walls

$$Q = U * A * CLTD \quad (6)$$

Where,

Q = Cooling load through the roof or wall (kW/HR); U = coefficient of heat transfer in roof; A = Area of the roof on walls; $CLTD$ = Cooling load temperature difference ^{0}C.

b.) Solar Load through Glass

$$Q = A * SHG * SF * CLF \quad (7)$$

Where,

A = Area of glass in m²; SHG = Solar heat gain; SF = Shade factor; CLF = Cooling load factor.

Internal Cooling Load consists of sensible and latent heat transfer due to occupants, products, appliances and light.

a.) People

$$Qsensible = N * QS * CLF \quad (8)$$

$$Qlatent = N * QS \quad (9)$$

Where,

N = Number of people; QS and QS and Q = Sensible and latent heat gain; CLF = Cooling load factor.

b.) Lights

$$Q = 3.14 * W * FUT * FSA * CL\text{F} \quad (10)$$

Where,

W = Watts input from electrical lighting load; FUT = Lighting use factor; FSA = Specific ballast allowance factor; CLF = Cooling load factor.

c.) Power Loads

$$Q = 2545 * P/EFF * FUM * FLM \quad (11)$$

Where,

P = Horse power rating from electrical power; EFF = Equipment motor efficiency; FUM = Motor use factor; FLM = Motor load factor.

Infiltration Air

$$Qsensible = 1.10 * CFM * (T^0 - T^1) \quad (12)$$

$$Qsensible = 4840 * CFM * (W^0 - W^1) \quad (13)$$

$$Qtotal = 4.5 * CFM * (h^0 - h^1) \quad (14)$$

Where,

CFM = Infiltration air flow rate; $T^0 - T^1$= Outside and inside dry bulb temperature; $W^0 - W^1$= Outside and inside humidity ratio; $h^0 - h^1$= Outside and inside air enthalpy.

Ventilation Air

$$Qsensible = 1.10 * CFM * (T^0 - Tc) \quad (15)$$

$$Qlatent = 4840 * CFM * (W^0 - Wc) \quad (16)$$

$$Qtotal = 4.5 * CFM * (h^0 - hc) \quad (17)$$

Where,

T^0= Outside dry bulb temperature; Tc = Dry bulb temperature of the air leaving the cooling coil; W^0= Outside humidity ratio; Wc = Humidity ratio of air leaving the coil; h^0= Outside and inside air enthalpy; hc = Enthalpy of air leaving the enthalpy coil.

The thermal performance of any building structure and its contents is represented by the building load. To maintain the designed indoor thermal comfort conditions, the heat gain or lose through the building, internal heat loads, ventilation and infiltration are considered in the load calculation.

Cost Analysis of the Design

Table 4 Material Cost of the Solar Hybrid Air-conditioner

S/N	Materials	Quantity	Unit Cost (₦)	Total Cost (₦)
1	Battery	1	48,000	48,000
2	Refrigerant	1	7,000	7,000
3	Condenser	1	2,500	2,500
4	Evaporator	1	2,500	2,500
5	Compressor	1	15,000	15,000
6	Inverter	1	90,000	90,000
7	Capillary Tube	1	800	800
8	Solar Panel	2	30,000	60,000
9	Evaporator Fan	1	3,000	3,000
10	Paint	1	4,000	4,000
11	1/4 South Africa Copper Coil	1	16,000	16,000
12	Drier	1	1,200	1,200
13	Refrigerant Oil	1	800	800
Total				250,800

Table 5 Labor and Overhead Cost

S/N	Type of Labor	Amount
1	Fabrication and Assembling Cost	28,000
2	Transportation and Miscellaneous	18,000
3	Total Labour Cost	23,000
Total		69,000

3. RESULTS AND DISCUSSIONS

The monthly averaged insolation values for horizontal surfaces in Uturu, Abia State, Nigeria (in this case, a horizontal solar PV array) were extracted. For the years 1980 to 2000 and 2000-2020 the monthly mean dry bulb temperature and relative humidity using Uturu, Abia State as a case study were recorded (Table 6).

Table 6 Average Humidity and dry bulb temperature for Abia State Nigeria (1980–2000 & 2000–2022).

Period	1980–2000		2000–2022	
Month	RH (%)	T_{db} (°C)	RH (%)	T_{db} (°C)
Jan	72.0	26.6	70.2	27.8
Feb	68.5	28.4	66.0	29.5
Mar	71.5	28.1	70.3	29.0
Apr	74.5	27.6	75.0	28.9
May	78.5	26.9	78.0	28.0
Jun	82.5	25.6	80.1	26.5
Jul	82.5	24.5	24.5	25.9
Aug	82.5	23.9	84.0	25.0
Sep	82.0	25.1	81.2	26.1
Oct	81.0	25.9	78.5	27.0
Nov	76.5	26.4	76.1	28.1
Dec	73.5	25.8	70.3	27.5
Annual	77.1	26.2	76.0	27.4

It is worth noting that the average dry bulb temperature in Table 6 (which is calculated over 24 hours per day for the month) is lower than the daytime dry bulb temperature (which is calculated from sunrise to sunset). The result depicts the equivalent monthly mean daily sun irradiations on a horizontal surface. From the lowest irradiance month in August to the highest irradiation month in April, the monthly mean daily sun irradiation data for the site range between 3.3 and 4.9 kWh m^2. From Figure 3, the coefficient of performance (COP) changes as the temperature outside changes. However, because COP curves/values from manufacturers' data are unavailable, an average COP value of 3.52 is utilized to produce the electrical load profile for the air conditioner.

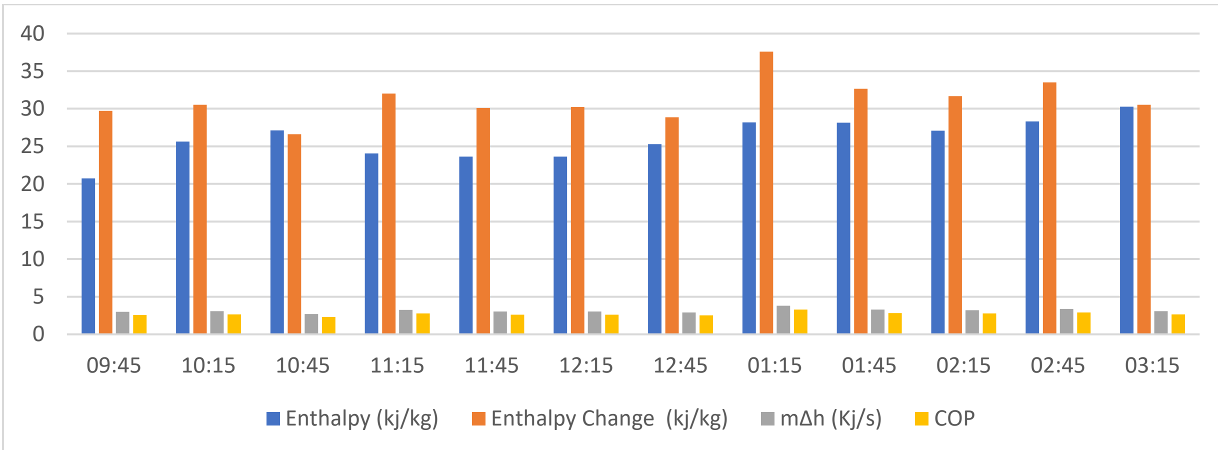


Figure 3 Coefficient of Performance with Time

4. CONCLUSIONS

The performance of a solar hybrid-powered air conditioner for cooling in hot humid conditions has been investigated in this project, which includes a case study in Uturu, Abia State, Nigeria. For an air conditioner with a nominal cooling capacity of 2.5 kW and maximum power usage of roughly 1.19 kW, a solar PV system with 1219489.32 Wp, 24 V battery setup has a monthly mean solar fraction of 71%. The 1040 Wp solar PV system generates roughly 1211 kWh of electricity per year, according to calculations. Also, its predictions and the corresponding actual cooling rate are greater than those of conventional ones. The introduction of solar hybrid air-conditioning system tends to solve problems such as economics of maintenance and operation, indoor air quality, environmental factors, energy-saving techniques and so on in conventional air conditioning systems.

Ethical issues

Not applicable.

Informed consent

Not applicable.

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This study has not received any external funding.

Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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