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Assessing the Influence of Solar Ventilation on Cabin TVOC Concentrations in Vehicles Parked under Sunlight

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Abstract

This study investigates the impact of solar ventilation systems on cabin air quality and temperature in vehicles exposed to prolonged sunlight. The experiment was conducted in September, a period characterized by high solar radiation, at the Occupational Health and Safety Institute of the Vocational Training Corporation in Amman, Jordan. Two identical vehicles were used—one equipped with a solar ventilation system and one without. Key parameters such as volatile organic compounds (TVOCs) and cabin temperature were monitored throughout the day. Results indicated that the car with solar ventilation had, on average, a 30% lower cabin temperature. The non-ventilated vehicle recorded a peak temperature of 59.2°C, compared to 41.7°C in the ventilated vehicle, with an average temperature difference of 15.5°C. Furthermore, the maximum TVOC concentration in the non-ventilated vehicle reached 30 ppm, while it remained at 9 ppm in the ventilated vehicle. On average, the total TVOC level in the car without solar ventilation was 3.1 times higher than in the car with the system. The greatest performance of the solar ventilation system was observed during the afternoon hours, when solar radiation was at its peak. These results highlight the effectiveness of solar ventilation systems in reducing cabin heat and pollutant accumulation, contributing to enhanced air quality, thermal comfort, and passenger safety.

Keywords: VOC emission, Vehicle thermal comfort, Air Quality, Solar ventilation.

Nomenclature

AC	Air-Conditioning
ACPH	The Air Change Per Hour
BC	Black Carbon
C	Capacity of the Battery (Ah)
CFM	Cubic Feet Per Minute (ft^3/min)
D	Battery Discharge Depth
E_D	Daily Average Electricity Consumption(kWh/day)
HC	Hydrocarbons
HCHO	Formaldehyde
IAQ	Interior Air Quality
I_{mp}	Peak Power Current (A)
Isc	Current (Short-Circuit) (A)
N	Storage Duration (Days)
NOx	Nitrogen Oxides
P	Power (W)
PM	Particulate Matter
P_{pv}	PV Rated Power (kW)
ppm	Parts Per Million
Q	Airflow Rate (m^3/hr)
Q_h	Heat-Quantity (kJ)
t	Time (s)
Ta	Outside Air Temperature (°C)
T_c	In-Cabin Temperature (°C)
T_e	Transferred Energy(W/m2)
TVOCs	Total Volatile Organic Compounds
V_c	Voltage (V)
VLT	Visible Light Transmittance
Voc	Voltage (Open Circuit) (V)
VOCs	Volatile Organic Compounds (ppm)
WHO	World Health Organization
SVOCs	Semi-Volatile Organic Compounds

1. Introduction

The use of fossil fuels is the primary source of greenhouse gas emissions, which are the leading cause of global warming. Solar photovoltaic (PV) technology is one of the fastest-growing renewable energy solutions and presents a strong alternative to fossil fuels due to its adaptability and broad application potential [1-3]. Indoor air quality (IAQ) in vehicles is crucial for health, particularly for individuals who spend extended periods inside vehicles due to their occupation. However, most research to date has focused on direct emissions, with limited attention to the chemical processes occurring within vehicle cabins [4].The greenhouse effect is a

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phenomenon in which shortwave solar radiation penetrates a vehicle's glazing and body, allowing sunlight to enter and be absorbed by interior components such as the dashboard, seats, floor, and steering wheel, these components, with higher thermal capacities than air, absorb and retain heat, subsequently releasing long-wave radiant energy, as shown in Figure 1, long-wave radiation is blocked by the car's glazing, causing heat to build up inside, this effect is more pronounced when the car is parked in direct sunlight [5].

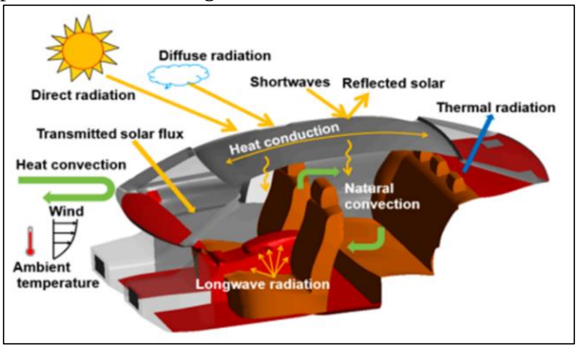

Figure 1. Greenhouse effect inside the car cabin [6].

Vehicles parked under direct sunlight can rapidly overheat, as illustrated in Figure 2 causing the interior air temperature to increase by 20 to 30 °C above the outside temperature [7].The rise in the interior temperature of a car cabin has several negative effects, such as higher fuel consumption, increased emission levels, and reduced thermal comfort [8].When a car is left in the sun for long periods, its interior temperature rises, leading to discomfort for passengers. To cool the car, drivers frequently use maximum air conditioning, which adds thermal load, strains the system, and increases fuel consumption [9], public awareness of the greenhouse effect in vehicles is vital to reducing hyperthermia-related deaths, especially in children left inside hot cars,this initiative aims to enhance safety and prevent such incidents [10].

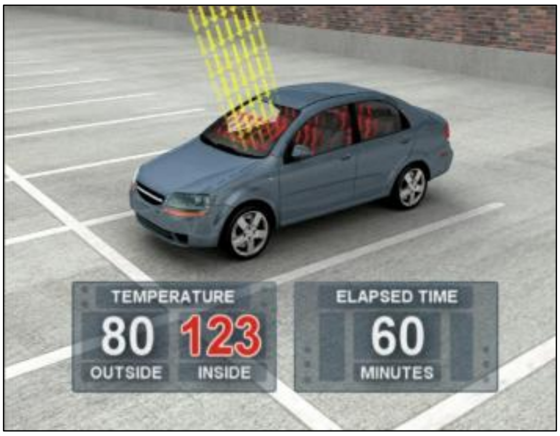

Figure 2. Rapid increase in cabin temperature [11].

Air quality is a critical health factor, particularly in enclosed spaces like vehicle cabins, where volatile organic compounds (VOCs) can accumulate to harmful levels. Poor in-cabin air quality has been linked to asthma, headaches, eye irritation, and even impaired driving performance. VOCs, often emitted from interior materials such as plastics, rubbers, textiles, and leather, are more concentrated indoors than outdoors. Prolonged exposure can affect the liver, kidneys, and nervous system, and increase cancer risk. Recognizing these risks, ISO 12219-1:2012 provides a standard method for measuring VOCs in vehicle interiors [12].

Numerous studies have measured VOCs in stationary parking and driving conditions. When driving conditions with different operational scenarios (air conditioning, natural ventilation, or a partially open window) are considered, the investigation of VOCs and total VOCs becomes a more pressing issue. Five different sedans from three manufacturers were used as an example to assess the content of individual and total VOCs (TVOCs). They experimented with static (parked, unventilated) and driving (air-conditioned, naturally ventilated) situations. The results showed that the TVOC level in static conditions is four to eight times higher than when driving [13]. Controlling the interior temperature of the car is one factor that affects the air quality within the vehicle. The internal temperature impacts the concentration of TVOCs inside the vehicle. The total volatile organic compounds (VOCs) rose by 42.7% between 30 and 40 °C and 58.5% between 40 and 50 °C. The car interior temperature can reach a maximum of 46 °C to 76 °C while in a static condition. The difference is greater than 20 °C compared to the surrounding temperature [14].

As interior temperature rises, the concentration of airborne chemicals diffusing from interior materials will rise as well [15]. The primary factor thought to contribute to a rise in interior temperature is solar radiation entering the car through the windshield or windscreen [16]. Interior surfaces like the steering wheel, dashboards, and seats will notice a sharp increase in temperature. The concentration of TVOCs generated by material emissions will therefore rise correspondingly. According to a study done in Malaysia, the dashboard has the highest interior temperature, which can reach 87.5 °C. They suggested sunshades, ventilators, and window tinting as three passive ways to lower interior temperatures, and they came to the conclusion that window tinting is the best strategy. These suggest that the influence of solar radiation within the car interior is inversely correlated with (VLT) levels. Everyone is quite concerned about the state of the air; according to a survey done on 300 Saudi and Omani citizens, 64 percent of people spend two to three hours each day in car cabins. The majority of individuals, nevertheless, don't give the air quality in these locations a lot of attention. According to several studies, indoor air can be significantly more contaminated than outside air in huge industrialized cities [17]. The World Health Organization (WHO) states that indoor air pollution seriously endangers people's health [18]. The World Health Organization considers in-car air a serious health risk due to high levels of VOCs and other pollutants. Up to 242 organic compounds have been detected in cabin air, varying by vehicle. Sun exposure raises cabin temperatures, accelerating material degradation and posing health risks like heat stroke. Most VOCs originate from plastics (e.g., polypropylene, polystyrene) and rubber or leather, which are used in components such as dashboards, seats, upholstery, and floor mats [13, 19].

The issue of air pollution from vehicles has become a major public health concern on a global scale, especially with regard to the volatile organic compounds (VOCs) that are emitted from within vehicles. Although research has shown that VOC production is temperature-dependent, it is unclear how sun radiation affects the distribution of VOCs in confined spaces like cars [20, 21]. It is not well known how solar radiation affects the distribution of volatile organic compounds in enclosed cabin space. We used a laboratory airship to forecast heat transfer combined with natural convection, heat conduction, and radiation, and we assessed the model's performance using various combinations of turbulence and radiation models. To simulate the spatial distribution of volatile organic compounds (VOCs), an emission model was utilized. The distribution of temperatures within the cabin is influenced by solar radiation, as demonstrated by our findings, which indicate that direct sun exposure can raise cabin temperatures by 30 °C and shaded surfaces by 10 °C. The dashboard and rear board, which are hotter interiors, emitted more volatile organic compounds (VOCs) per unit of time and area because of the high temperature dependence. The thermal buoyancy flow caused a volatile organic compound plume to rise from the inner sources. The interiors emitted 19 mg of VOCs in total throughout the course of two simulated hours, from 10:00 a.m. to noon. The results, which include predicted spatial distributions of volatile organic compounds (VOCs), provide automobile manufacturers, who are increasingly concerned about the cabin environment and the health of drivers and passengers, with a valuable resource [20]. The study found elevated VOC levels in older metro carriages, with underground concentrations of acetone and acrolein exceeding above-ground levels by 10%. These levels increased with commuter density, reaching up to 26.2 $\mu g/m^3$ [22]. The study reported average VOC concentrations ($\mu g/m^3$) as follows: benzene (16.73), toluene (66.0), xylene (14.2), ethylbenzene (6.7), styrene (28.09), formaldehyde (16.4), acetaldehyde (12.4), and acetone (20.6). VOC levels were higher in new vehicles and those with leather interiors[23].

The in-cabin microenvironment is a source of hazardous air pollutants, which are mostly caused by interior material emissions, fuel leaks, exhaust fume leaks, and penetration from outside the vehicle. A wide variety of car cabin designs has resulted in significant variations in the types, concentrations, and rates of in-cabin pollutants, and therefore in the levels of personal exposure. Vehicles with various interior structures, ventilation configurations, interior cabin furnishings, etc. were designed by As a result, variations in vehicle cabin properties have an effects on indoor vehicle pollution. The common species of air pollutants, their sources, and the movement of air pollutants under various ventilation conditions are depicted in Figure 3. When a car is newly produced, the in-cabin pollutant concentrations are frequently high due to high interior temperatures or poor air exchange rates [24]. Study investigated how vehicle interior components affect cabin odours and VOC emissions. Five materials were tested in controlled chambers, with seats and door panels identified as the main odours contributors. They significantly increased odours intensity and similarity, while weather-strips had a masked effect. Eleven key odours compounds were identified, with door panels, seats, and weather-strips responsible for 58%, 26%, and 16% of odours-related substances, respectively. These findings help guide material choices to reduce in-vehicle odour's [25].

Concerns about air quality in confined environments, like car cabins, are on the rise, but there's still a lack of focused research on reducing TVOCs in these spaces, this study addresses this gap by investigating two main points: (1) the impact of temperature on TVOC levels inside cars, and (2) how well a solar ventilation system can help improve air quality by reducing these compounds. The study also stresses the importance of implementing strict safety guidelines to tackle risks posed by overheated vehicles. Solving these problems has the potential to enhance vehicle performance and promote both environmental and safety standards.

The paper is organized as follows: Section 2 explains the methodology, including theoretical concepts, calculations, instrumentation, vehicle details, the experimental environment, setup, and methods for collecting and analyzing data. Section 3 outlines the results and their significance, while Section 4 concludes with a summary of the study's findings.

2. Method

2.1. Theory and calculation

The climatic analysis of the cabin refers to calculating heat transfer by taking into account conduction, convection, and radiation between the passengers and the cabin components. Figure 4 depicts the primary mechanisms influencing heat gain or loss [11].

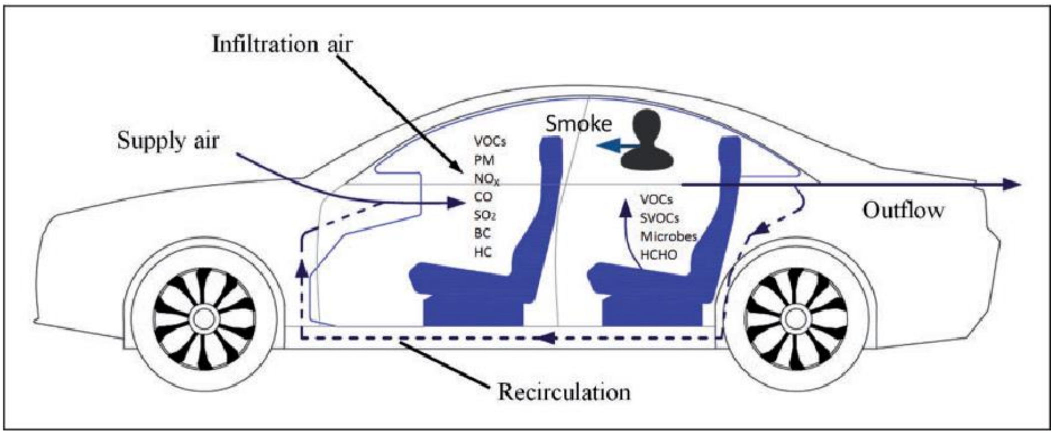

Figure 3. Air pollutant sources and their movement within the cabin [24].

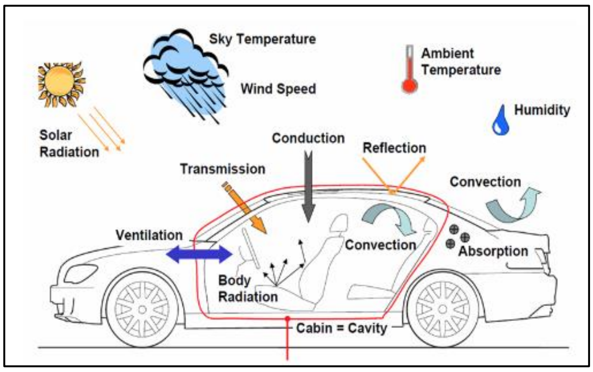

Figure 4. The main mechanisms that affect heat gains or losses [26].

The temperature within the car cabin is evaluated using equation (1), which determines the heat quantity based on the cabin's volume and the temperature difference between the interior and the outside environment. This equation aids in calculating the power needed for the proposed ventilation fan, as outlined below:

$$Q_h=\rho_a V C_a \Delta T \quad (1)$$

Where Q_h represents the cabin heat quantity (kJ), ρ_a is the density of air (kg/m³), V is the volume of the cabin (m³), C_a is the air specific heat (kJ/kg°C), and ΔT denotes the temperature variation (°C).

The heat quantity obtained from equation (1) is considered to be equal to the electrical energy needed by the system to remove a specific amount of hot air within a defined time frame. The formula for the necessary electrical work is given below:

$$W_e = IV\Delta t \quad (2)$$

In the above equation, W_e denotes the electrical work (kJ), I is the current (A), V represents the voltage supply (V), and Δt is the time (s) required to lower the temperature to the desired level (s).

The system operates on a 12V power supply. Chosen after assessing similar items in the market. After determining the time required to cool the cabin, the current (I) is measured and utilized in Equation (3) to compute the energy necessary for the fan to remove hot air from the vehicle.

$$P = V\,I \quad (3)$$

Where P denotes the power of the ventilation fan (W). I represents the current (A) and V is the voltage supplied (V).

To ascertain the necessary capacity of the solar panel, the average daily energy consumption in watt-hours (Wh/day) needs to be calculated using equation (4)

$$E_D = Pn \quad (4)$$

Where E_{ave} signifies the average daily energy consumption in watt-hours (Wh/day), P represents the power in watts (W) and n indicates the average daily operating hours (h/day).

The peak rated power of the photovoltaic (PV) array from equation (5) is utilized to calculate the power output of the solar panel necessary to satisfy electrical requirements.

$$P_{PV} = \frac{E_D}{SP\eta} \quad (5)$$

Where P_{PV} indicates the power of the photovoltaic system (kWp), E_D is the electricity consumption as average per day (kWh/day), SP refers to the value of peak sun hour per day, and η denotes the total efficiency of the system (%).

The capacity of the battery for the proposed system is calculated using Equation (6)

$$C = \frac{NE_D}{D\eta_{inv}} \quad (6)$$

Where C is the capacity of the battery (kWh). N represents the number of days the system can store energy, D indicates the allowable depth of discharge for the battery, and η_{inv} signifies the efficiency of the inverter (%).

2.2. Materials

An in-depth review of the experimental setup is provided in this section, including the materials and equipment used. The ventilation system's design and its influence on the cabin environment are discussed, along with the tools employed to measure temperature, humidity, and TVOC levels. Vehicle specifications are also covered, with an emphasis on features that could influence thermal dynamics and VOC emissions, contributing to the reliability and repeatability of the findings.

2.2.1. Solar ventilation system

Renewable energy systems, especially those utilizing solar power, are advancing at an impressive rate due to the ongoing depletion of fossil fuel reserves. Solar energy, being clean, abundant, and renewable, is effectively harnessed through photovoltaic (PV) technology[35]. This experiment utilized a solar-powered ventilation system to decrease the temperature inside the vehicle cabin and improve airflow. By reducing TVOC concentrations, the system enhances both air quality and passenger safety. Its main components include a solar photovoltaic panel, ventilation fan, thermostat, storage battery, and charge controller, as shown in Figure 5.

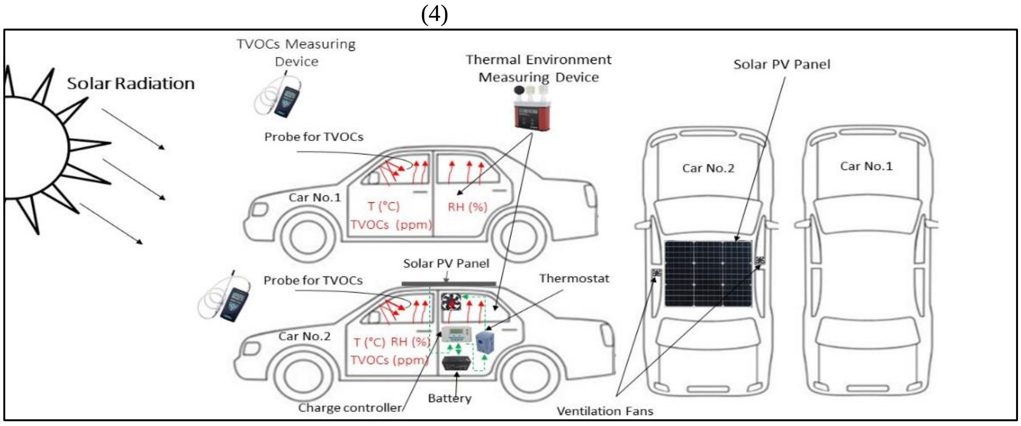

Figure 5. Proposed system configuration.

2.2.2. Thermal environment measurement device

Capable of measuring relative humidity, heat index, dry bulb temperature, wet bulb temperature, globe temperature, and wet bulb globe temperature WBGT, this device is suitable for both indoor and outdoor use. A comprehensive list of its specifications is included in Table 1.

Table 1. Thermal environment monitoring device specifications [27].

Model	QUES.Temp °46.
Measurements	Dry bulb temperature (°C), relative humidity (%), wet bulb temperature (°C), globe temperature (°C), heat index, WBGT indoors (°C), and WBGT outdoors (°C).
Operating temperature range	Sensor assembly: -5 to 100 °C.
Accuracy	Tdp and TG: ±0.5°C between 0 and 120°C.RH: ±0.5°C between 20 and 95%.

2.2.3. Volatile organic compound measuring device

The VOC monitor is designed for on-site measurements in applications such as industrial safety, environmental monitoring, and indoor air quality assessment. The specifications for the device used in this study are detailed in Table 2.

Table 2. VOC monitoring device specification [28].

Model	XP-3120-V
Gas Detected	VOC
Detection Principle	Hot-wire semiconductor
Weight	Approx. 450g
Operation Temperature	0 to +40 °C
Dimensions	W82 x H162 x D36 mm
Detection Range	Low range: 0 to 100 ppm High range: 0 to 1000 ppm.

The following Figure 6 illustrates the volatile organic compound measuring device used in our experiments.

Figure 6. Volatile organic compound measuring device.

2.2.4. Experiment location and climate

The experiment was conducted in Institute of Safety-Vocational Training Corporation /Amman, the capital city of Jordan, located at 31°N latitude and 35°E longitude. Amman's position in the highlands near the Mediterranean climate zone [29].

The Figure 7 presents the average climatic conditions at the experimental site during the experiment period, including average day and night temperatures and solar irradiation levels. The site experiences a Mediterranean climate with hot, dry summers, making the selected period ideal for evaluating thermal build-up in vehicle cabins. During the experiment, the average daytime temperature reached 32.5°C, while nighttime temperatures averaged 18.5°C, indicating a significant difference between day and night conditions.

The solar irradiation, represented as direct normal irradiation (DNI), was approximately 239.5 kWh/m², reflecting the high solar energy input typical of this season. This combination of elevated temperatures and strong solar radiation was deliberately chosen to maximize the greenhouse effect inside the vehicle cabin, ensuring a worst-case scenario to test the effectiveness of the solar ventilation system in reducing cabin temperature and TVOC concentrations.

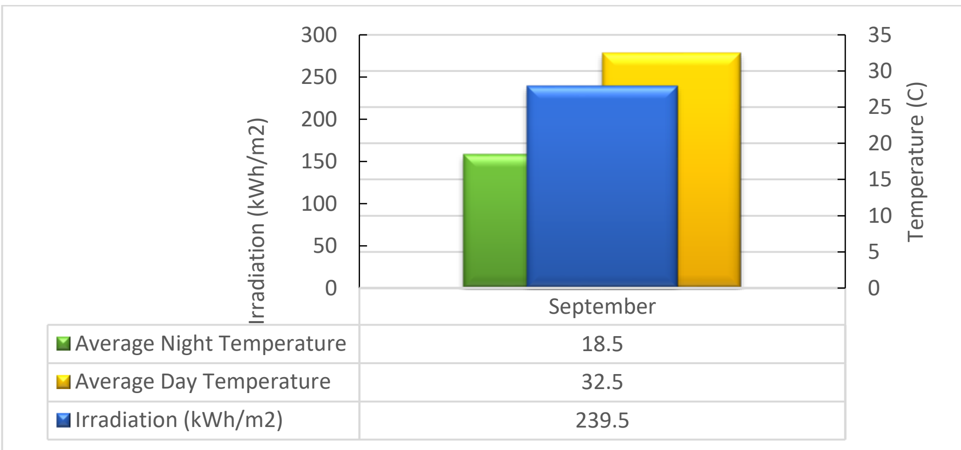

Figure 7. Monthly Average Direct Normal Irradiation[30].

2.2.5. Experimental set-up

The experimental setup, depicted in Figure 8, is designed to assess the influence of a solar ventilation system on cabin TVOC concentrations and cabin temperature in vehicles exposed to sunlight. Two cars are used in the experiment, and both were parked facing the south direction to ensure maximum exposure to sunlight and represent a worst-case scenario for thermal build-up:

Car No. 1 is equipped with a solar ventilation system comprising a PV panel, a charge controller, a battery, a thermostat, and a ventilation fan. The technology utilizes solar energy to power the fan, promoting air circulation and potentially lowering the temperature and TVOC concentrations within the cabin. Car No. 2, which does not have a solar ventilation system, is used as a control to examine the natural accumulation of heat and TVOCs in a vehicle without active ventilation.

Under direct sunlight, the cabin conditions of both vehicles are monitored using two types of instruments: one to measure TVOC concentrations and another to record cabin temperature. The goal of the experiment is to analyze the differences in air quality and temperature between Car No. 1, which is equipped with a solar ventilation system, and Car No. 2, which serves as a control without ventilation, providing insights into the system's ability to mitigate heat and harmful emissions.

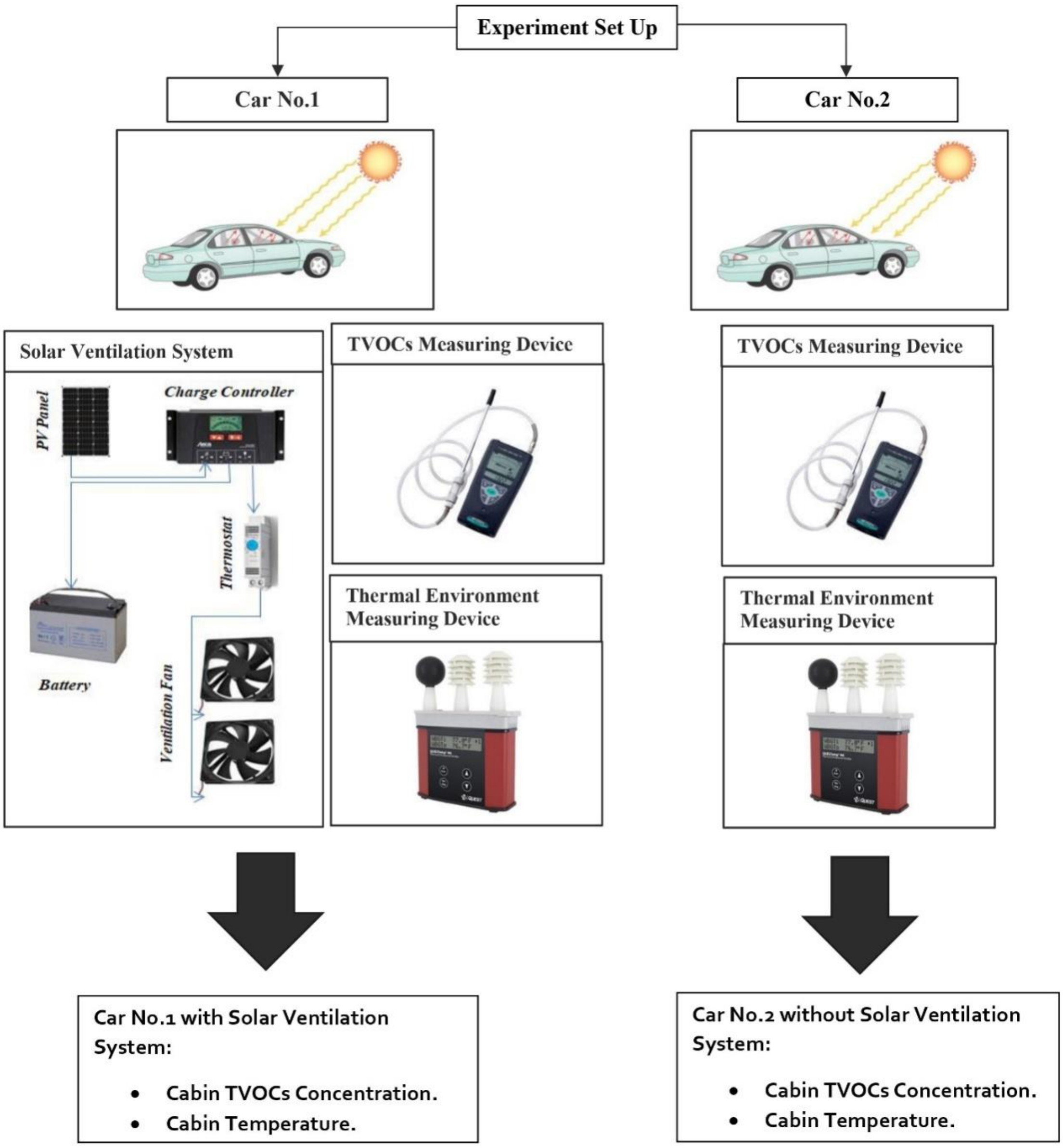

Figure 8. Experimental set-up.

2.2.6. Experiment process flow

The experimental procedure for this experiment was conducted using two identical vehicles Table 3. Below, which shows the specifications of the cars used in the experiment, one equipped with a solar ventilation system and the other without, the setup involved installing a PV panel on the roof of Car No.1, as part of the setup, as illustrated in Figure 7, to power two fans installed inside the cabin, the system also included a charge controller, a storage battery, and a thermostat to regulate the cabin temperature. A TVOC probe was placed inside the cabin of both vehicles to measure the TVOCs, while a thermometer was used to record the temperature. Car No.2 was left without any ventilation system, Figures9-11 shown the configuration of the proposed system outside the car cabin.

Parked in an open area with direct sunlight exposure, both vehicles were monitored over several days. Data was collected daily between 9:00 am and 2:00 pm, with hourly measurements of TVOC concentrations and cabin temperatures. Baseline measurements were taken in each vehicle before the experiment started. The solar ventilation system in Car No. 1 operated autonomously during the experiment, using energy generated by the PV panel to power the fans and circulate cabin air. Car No. 2, by contrast, had no ventilation system, resulting in a natural buildup of heat and TVOCs.

2.2.7. Data collection and analysis

Data in the current study were collected for two distinct experiments, each of which examined different factors affecting total volatile organic compounds (TVOCs) emissions and cabin temperature. Data were recorded hourly from 9:00 am to 2:00 pm over several.The reliability and accuracy of the experimental results were verified by comparing the results of the current study with previous studies to ensure consistency with the results found in the field. In addition, the experiments were achieved in several independent repetitions. And results are presented as the mean ± standard deviation (SD) based on these replicates. Finally, a two-way ANOVA was conducted using Graph Pad Prism to evaluate differences among the variable groups, statistical significance was defined as a P-value less than 0.05, statistically significant differences are indicated as follows: ****$P \leq 0.0001$, ***$P \leq 0.001$, **$P \leq 0.01$, and *$P \leq 0.05$, Overall, the data analysis provides insights into the effects of sunlight exposure and interior materials on cabin air quality and temperature

Table 3. Experimental cars specifications

Car Make	KIA- Sephia
Brand	Korea
Interior volume	90 ft^3
Colour	Blue
Interior seats materials/colour	Fabric / Grey
Qty	2

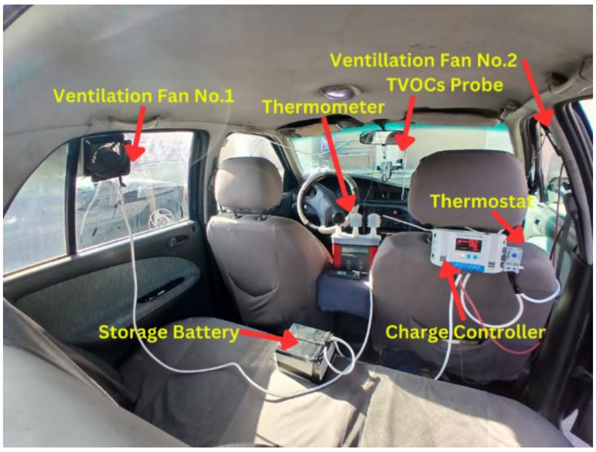

Figure 9. Configuration of the proposed system inside the car cabin.

Figure10. Configuration of the proposed system inside the car cabin (front view)

Figure 11. Configuration of the proposed system outside the car cabin (side view)

3. Results and Discussion

Temperature plays a crucial role in determining TVOC emissions within car cabins. This study conducted a series of experiments to evaluate how rising temperatures, driven by the greenhouse effect in cars parked under direct sunlight influence on in-cabin air quality, also it assessed the effectiveness of a solar ventilation system in mitigating this effect, two identical cars were exposed to direct sunlight one equipped with a solar ventilation system and the other without. Hourly data were collected from 9:00 am to 2:00 pm over several days, measuring cabin air temperature, TVOC concentrations, and ambient temperature for both vehicles.

3.1. Car cabin air temperature, relative humidity and TVOC concentration in vehicles without and with solar ventilation systems

The Figure 12, indicates a significant relationship between ambient temperature, cabin temperature, and TVOC concentrations, the ambient temperature fluctuates between 22°C and 28°C, over the observation period, demonstrating daily variations typical of outdoor environmental conditions, as well as, the cabin temperature exhibits a much higher range, peaking at approximately 55°C to 60°C. This discrepancy underscores the greenhouse effect inside the vehicle, where solar radiation penetrates through windows, causing a substantial rise in internal temperatures compared to the external environment, the TVOC concentrations within the vehicle cabin show a strong correlation with cabin interior temperature. As cabin interior temperatures rise, TVOC concentrations also increase, reaching values as high as 30 ppm. This phenomenon results from the heat-activated release of VOCs by interior materials, such as plastics and upholstery, which intensify emissions at higher temperatures. The daily cycle of TVOC levels aligns with temperature fluctuations, peaking during the day's hottest moments. This relationship shows how ambient temperature indirectly influences VOC concentrations by heating the car's cabin, highlighting the compounded effects of solar radiation on both interior temperatures and air quality.

Figure 12. Car cabin, ambient temp and TVOC concentration in car (without solar ventilation)

The use of a solar ventilation system results in marked improvements in maintaining cabin temperature and air quality. Although ambient temperatures range from 22°C to 28°C, consistent with external fluctuations, the cabin temperature is notably reduced, with peaks ranging between 38°C and 42°C. This indicates the effectiveness of the solar ventilation system in alleviating the greenhouse effect within the vehicle by facilitating heat dissipation. As illustrated in Figure 13, the reduction in cabin temperature has a direct impact on TVOC concentrations, which peak at approximately 6 ppm substantially lower than the levels observed without ventilation. The results show that the solar ventilation system sufficiently minimizes volatile organic compound emissions by lowering cabin temperatures, which drive material emissions. Although the diurnal patterns of TVOC levels and cabin temperature remain, their magnitudes are notably reduced due to the steady airflow provided by the system. This demonstrates the dual advantage of solar ventilation: decreasing heat accumulation and reducing harmful emissions inside the vehicle. These findings reinforce the value of solar ventilation systems in improving passenger safety and comfort by mitigating heat and air quality issues in sun-exposed vehicles.

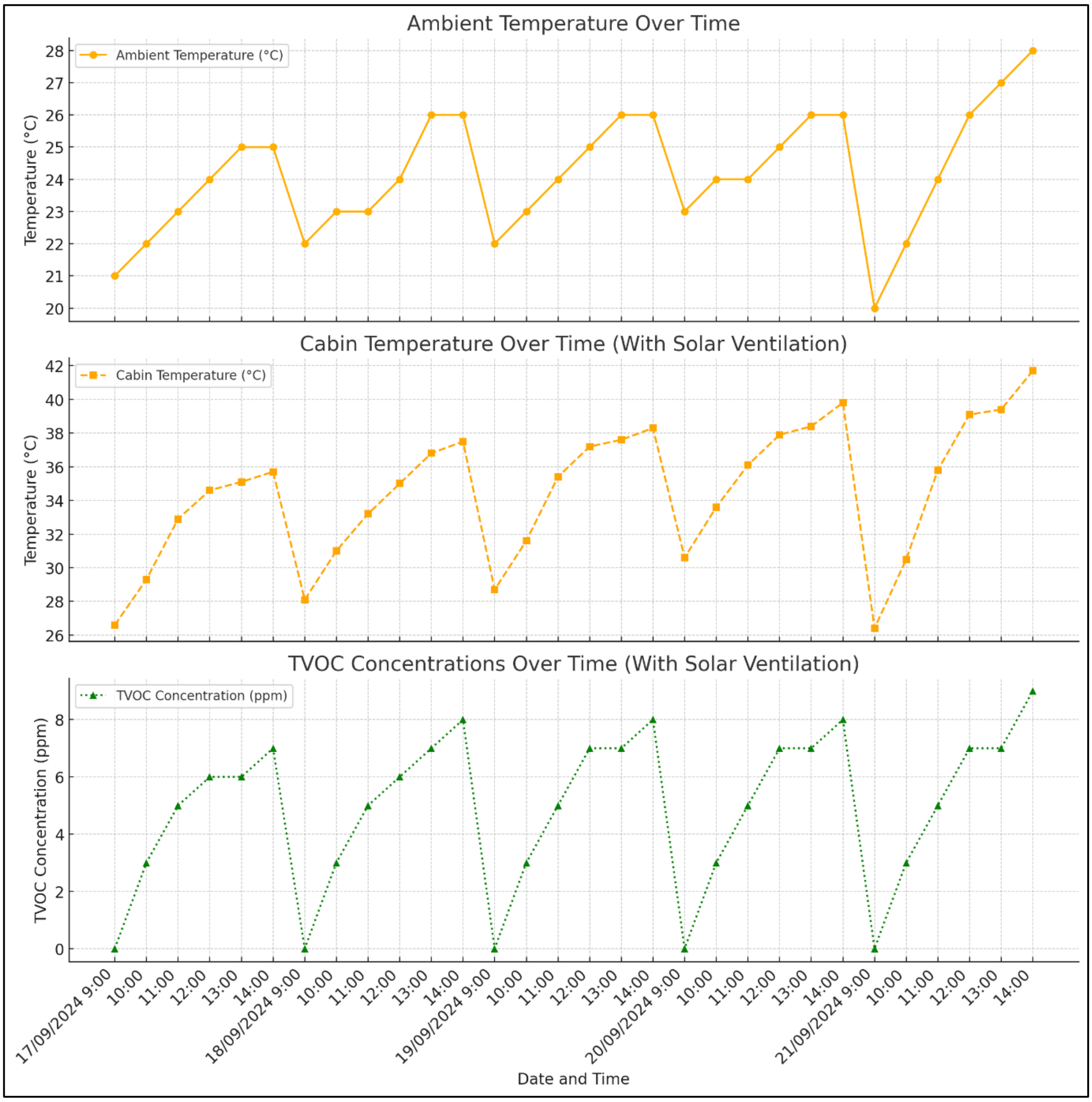

Figure 13. Car cabin, ambient temp and TVOC concentration in car (with solar ventilation).

The relationship suggests that ambient temperature indirectly influences TVOC levels by raising cabin temperatures. This highlights the compounded effect of solar radiation on both thermal and air quality conditions inside parked vehicles. It emphasizes the need for interventions, such as solar ventilation systems, to mitigate heat build-up and reduce TVOC emissions, thereby enhancing passenger safety and comfort, in the absence of a solar ventilation system Figure 14, the cabin temperature consistently exceeded the ambient temperature throughout the day, demonstrating a pronounced greenhouse effect, at 9:00 am, the cabin temperature was 39.2±2.0°C, while the ambient temperature was 21.6±1.1°C, by 10:00 am, the cabin temperature rose to 46.7±2.3°C compared to an ambient temperature of 22.8±0.8°C, at 11:00 am, the cabin temperature reached 48.4±3.2°C, while the ambient temperature was 23.6±0.6°C, by 12:00 pm, the cabin temperature climbed to 52.3±2.7°C, with the ambient temperature at 24.8±0.8°C, by 1:00 pm, the cabin temperature climbed to 53.5±2.4°C, with the ambient temperature at 26.0±0.7°C, the temperature peaked at 54.9±3.4°C at 2:00 pm, while the ambient temperature stabilized at 26.2±1.1°C, the error bars indicate minor variations in measurements, likely due to environmental factors, but the trend consistently highlights the significant heat build-up in the cabin, underscoring the need for solutions to mitigate this effect.

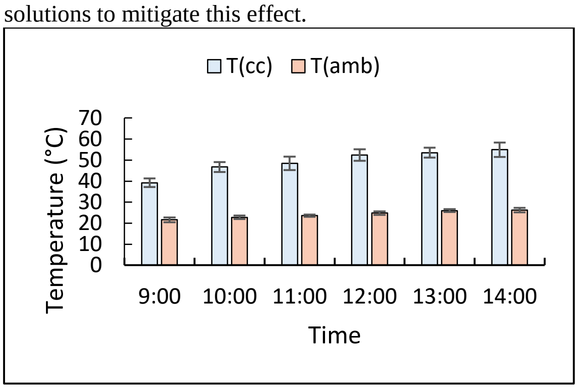

Figure 14. Hourly temperature profiles of a car cabin and ambient environment without solar ventilation

The vehicle shown in Figure 15, equipped with the ventilation system, maintained a cabin temperature close to ambient conditions all day, underscoring the benefits of solar ventilation in combating the greenhouse effect. At 9:00 am, the cabin temperature was 28.1±1.7°C, while the ambient temperature was 21.6±1.1°C, by 10:00 am, the cabin temperature was 31.2±1.6°C compared to an ambient temperature of 22.8±0.8°C, at 11:00 am, the cabin temperature reached 34.7±1.5°C, while the ambient temperature was 23.6±0.6°C, by 12:00 pm, the cabin temperature increased slightly to 36.8±1.9°C, with the ambient temperature at 24.8±0.8°C, by 1:00 pm, the cabin temperature reached 37.5±1.6°C, with the ambient temperature at 26.0±0.7°C. The temperature peaked at 38.6±2.2°C at 2:00 pm, while the ambient temperature stabilized at 26.2±1.1°C, solar ventilation significantly reduces cabin heat build-up, demonstrating its thermal benefits.

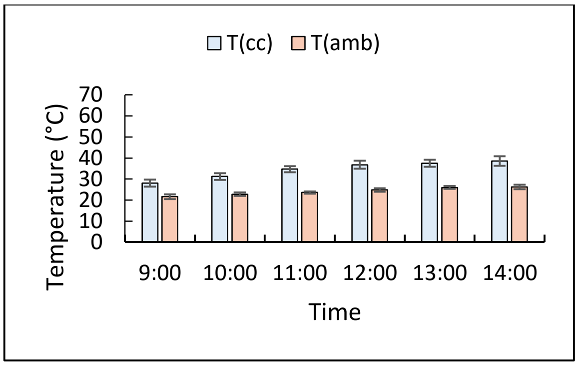

Figure 15. Hourly temperature profiles of a car cabin and ambient environment without solar ventilation.

The Figure 16, illustrates the relative humidity in a car parked under direct sunlight without solar ventilation system. The relative humidity decreases significantly over the same period, dropping from around 35% at 9:00 am to approximately 10% at 2:00 pm. This clear inverse relationship between temperature and humidity demonstrates the impact of direct sunlight on the car cabin environment, where increased heat leads to rapid moisture evaporation and a decline in relative humidity.

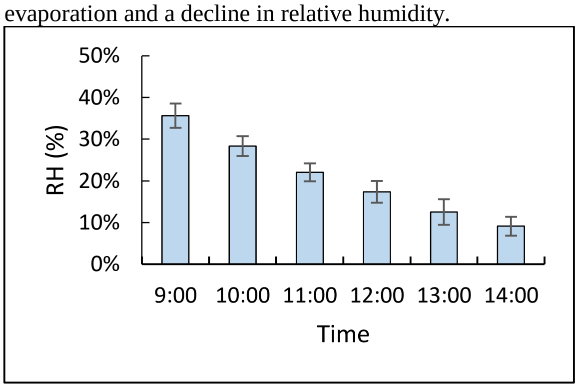

Figure 16. RH in a car under sunlight / without solar ventilation

The Figure 17 shows the relative humidity in a car with solar ventilation system. The relative humidity fluctuates within a narrow range, maintaining levels between 25% and 35% throughout the observation period. This consistency highlights the moderating effect of solar ventilation system, which prevents excessive heating and helps maintain a balanced humidity level, providing a more stable environment compared to the car exposed to direct sunlight

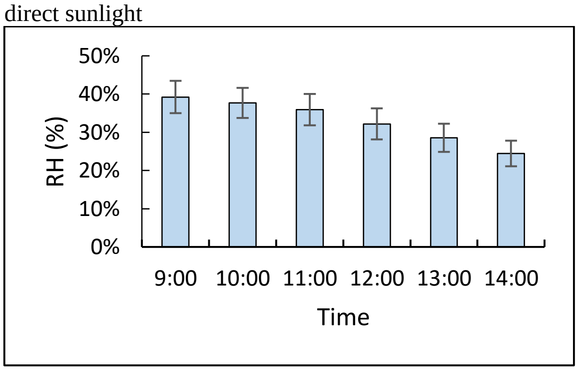

Figure 17. Relative humidity in car with solar ventilation system.

The Figure 18 illustrates the variations in TVOC concentration within a vehicle exposed to direct sunlight and devoid of a solar ventilation system. At 9:00 am, the TVOC concentration is 6 ± 0.5 ppm; by 10:00 am, it climbs to 9 ± 0.7 ppm, indicating that prolonged exposure to sunlight elevates the internal temperature of the vehicle, resulting in heightened emissions of volatile organic compounds from interior components, At 11:00 am, the TVOC level attains 20±1.3 ppm, signifying a substantial increase relative to prior readings. By midday, the TVOC concentration increases to 24±1.5 ppm, indicating the cumulative impact of heat exposure. The readings stabilize somewhat following this juncture, with TVOC levels attaining 26±1.3 ppm by 1:00 pm and seeing a minor rise to 28±1.5 ppm at 2:00 pm. The figure depicts the correlation between prolonged sunlight exposure without solar ventilation and the increase in TVOC concentration within the vehicle cabin. Underscoring the imperative to restrict direct sunlight exposure to reduce the build-up of potentially hazardous volatile compounds, this can affect air quality and provide health risks to residents.

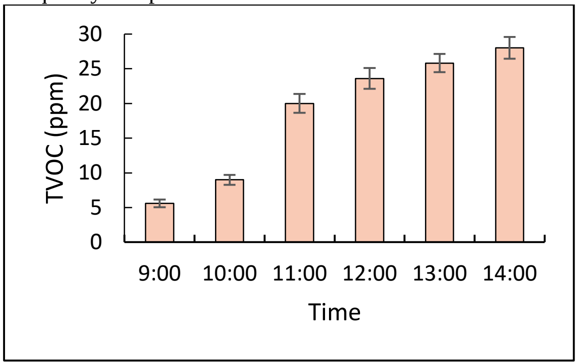

Figure 18. Hourly TVOC profiles of a car cabin / without solar ventilation.

Figure 19 shows that the solar ventilation system reduced vehicle TVOC) content. At 9:00 am, the TVOC concentration starts at 0 ppm. By 10:00 am, the concentration rises modestly to 3.0 ± 0.0 ppm, indicating that the solar ventilation system helps limit the accumulation of volatile organic compounds even as the vehicle remains exposed to sunlight, at 11:00 am, the TVOC level increases to 5.0 ± 0.0 ppm, reflecting a much lower rise compared to the scenario without solar ventilation, by noon, the concentration reaches 7 ± 0.5 ppm, showing a consistent but controlled trend, the values stabilize further after this point, with TVOC levels reaching 7 ± 0.4 ppm by 1:00 pm and slightly increasing to 8 ± 0.7 ppm at 2:00 pm. The figure shows how solar ventilation lowers car cabin TVOCs. This trend shows the system's function in enhancing cabin air quality and minimizing volatile organic compound health hazards, especially during prolonged sunlight exposure.

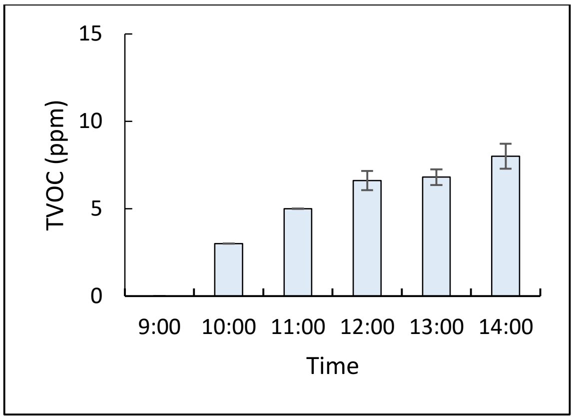

Figure 19. Hourly TVOC profiles of a car cabin / with solar ventilation.

3.2. *Comparison of car cabin temperature and TVOC concentration in cars with and without a solar ventilation system*

Figure 20, shows ambient and cabin temperature with and without solar ventilation over time. It shows how the solar ventilation technology lowers cabin temperatures in sunlight parked cars. The ambient temperature gradually increases throughout the day, starting at 21.6±1.1°C in the early morning and reaching around 26.2±1.1°C by 14:00, this reflects the natural heating pattern of the external environment due to solar radiation, the cabin temperature without solar ventilation is significantly higher, starting at 38.8±2.4°C in the morning and climbing to 54.9±3.4°C by 14:00, this increase is a result of the greenhouse effect, where solar radiation heats the interior of the car, and the lack of ventilation prevents heat dissipation, the steep rise in temperature indicates poor thermal regulation inside the vehicle when no ventilation system is present.

The cabin temperature with solar ventilation is significantly lower, starting at 28.1±1.7°C in the morning and peaking at 38.6±2.3°C at 14:00. The solar ventilation system decreases heat buildup by allowing continuous circulation in the car interior, reducing the greenhouse impact, This difference of 15–20°C between the without and with lines demonstrates the efficiency of the ventilation system in maintaining a more comfortable and safer interior environment, the comparison underscores the critical role of solar ventilation in improving thermal comfort and safety. While ambient temperatures remain relatively moderate, the sharp contrast between the cabin temperatures with and without ventilation highlights the severity of the greenhouse effect and the necessity of implementing ventilation systems in vehicles parked under sunlight.

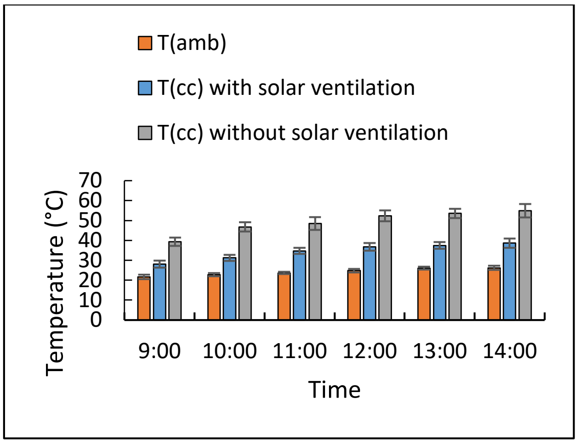

Figure 20. Comparison of temperatures between two cars with/without solar ventilation.

Figures 21 show the trend lines of cabin temperature variations in two vehicles: one without a solar ventilation system (red line) and the other with a solar ventilation system (blue line). The red line, indicating the vehicle without solar ventilation, exhibits markedly elevated cabin temperatures throughout the day, with a steeper trend line (slope: 70.491), underscoring the strong impact of the greenhouse effect. Conversely, the blue line, which signifies the vehicle equipped with solar ventilation, exhibits reduced cabin temperatures and a more gradual trend line (slope: 50.373), underscoring the efficacy of the solar ventilation system in alleviating heat accumulation.

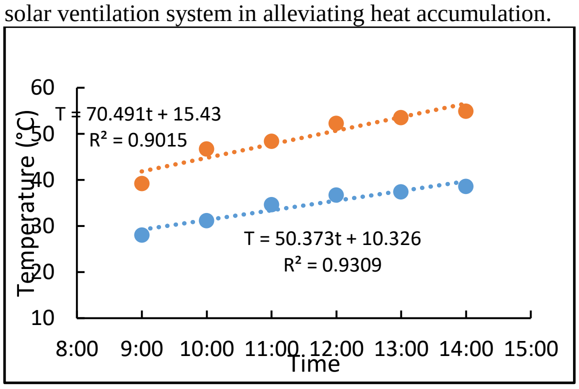

Figure 21. Cabin temperature trend line for a car with/without solar ventilation

Figure 22, shows how TVOC levels change over time in two situations: one car has a sun ventilation system, and the other does not. The data shows that the solar ventilation device effectively reduces TVOC emissions inside the car. In vehicles without solar ventilation, TVOC concentrations increase sharply as the day progresses, peaking at 28.0±1.6 ppm by early afternoon (14:00), this trend highlights the effect of rising cabin temperatures caused by prolonged exposure to sunlight, which accelerates the volatilization of interior materials, resulting in elevated TVOC levels, the consistent high values across different days indicate a persistent build-up of volatile organic compounds in the absence of ventilation.

In contrast, automobiles equipped with solar ventilation exhibit considerably lower TVOC concentrations throughout the day, reaching a maximum of 8.0±0.7 ppm. This decrease illustrates the efficacy of the ventilation system in sustaining airflow within the cabin, therefore dissipating heat and minimizing the volatilization of interior materials, the very gentle gradient of the green lines indicates that the solar ventilation system effectively maintains stable TVOC levels, even at peak daytime temperatures. The comparison underscores a distinct benefit of solar ventilation systems in diminishing hazardous emissions and enhancing cabin air quality. The persistent disparity between the red and green lines at all time intervals and days highlights the system's capacity to improve passenger safety and comfort in cars exposed to sunshine.

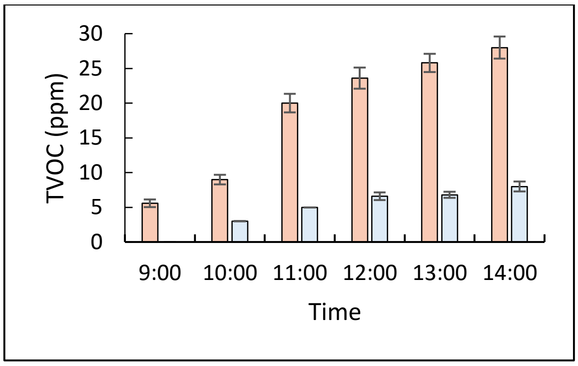

Figure 22. Comparison of TVOC concentrations between two cars with/without solar ventilation.

Figure 23 shows the linear trend of TVOC concentration increase over time for both ventilated and non-ventilated vehicles. The linear regression equations (R^2 = 0.9191 for the non-ventilated car and R^2 = 0.9174 for the ventilated car) demonstrate a strong correlation between time and TVOC buildup. These trends align with theoretical expectations for VOC accumulation in enclosed spaces under continuous heat and emission sources, which generally follow a linear or exponential increase depending on ventilation efficiency and source strength. The lower slope observed in the ventilated vehicle confirms the effectiveness of the solar ventilation system in slowing down VOC buildup.

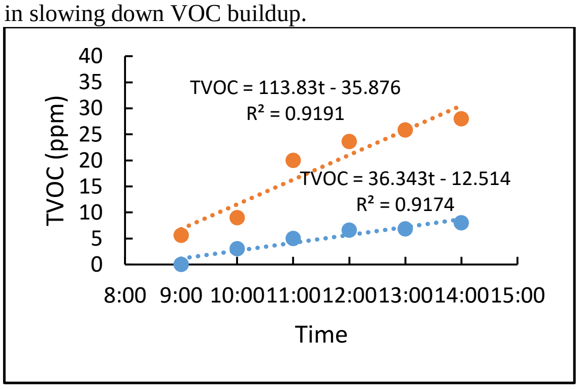

Figure 23. TVOC trend line in a car with/without solar ventilation.

The Figure 24, compares the performance of cars with and without solar ventilation. The car without ventilation shows higher TVOC levels and extreme temperature values, indicating stronger greenhouse effects and emissions. In contrast, the solar ventilation system effectively lowers both TVOC concentrations and cabin temperatures, maintaining a cooler and more stable interior environment, this highlights the system's role in improving air quality and thermal comfort in vehicles parked under sunlight.

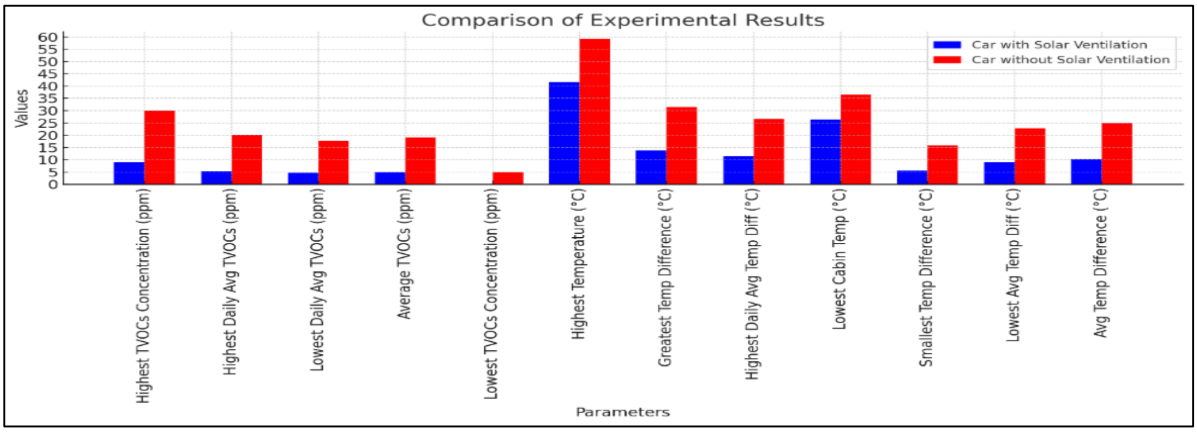

Figure 24. Comparison of experimental results.

The results show that solar ventilation systems are crucial for improving the air quality and temperature within the automobile, particularly in vehicles that are left in the sun for long periods of time. Passenger comfort is enhanced and the substantial health risks associated with prolonged exposure to VOCs in enclosed spaces are reduced as a result of the installation of a solar ventilation system, which significantly lowers cabin temperature and TVOC levels, solar ventilation systems enhance the healthiness of car cabins by minimizing the buildup of detrimental substances and sustaining lower temperatures, so mitigating the danger of respiratory ailments and other health concerns, Moreover, the implementation of such systems provides a significant opportunity for automotive manufacturers and regulators to enhance fuel efficiency, diminish greenhouse gas emissions, and promote passenger welfare. This study's findings offer critical insights for governments, automotive manufacturers, and academics, underscoring the necessity for forthcoming policies and technologies that emphasize human health and environmental sustainability.

3.3. Data Analysis Methods and Validation

This section delineates the methodologies employed to assess the experimental data and corroborate the findings. Figure 25 compares the inside temperatures of a vehicle parked in sunshine with and without a solar ventilation system. The data shows a significant reduction in internal temperature when the solar ventilation system is used, at all measured times, the internal temperature of the car without solar ventilation is substantially higher than that of the car equipped with the system, the statistical analysis reveals significant differences at all recorded time points, representing highly significant differences ($p < 0.0001$) during peak hours. This demonstrates the solar ventilation system's effectiveness in mitigating the greenhouse effect and significantly reducing cabin temperature, especially during periods of intense sunlight.

Figure 26 compares TVOC in a car with a solar ventilation system and one without when parked in sunlight. The solar ventilation system significantly reduces TVOC levels. At every assessed time interval, the vehicle without solar ventilation demonstrates significantly elevated TVOC levels in contrast to the vehicle equipped with the system. The statistical analysis indicates substantial changes across all recorded time intervals. With extremely significant differences ($p < 0.0001$) at peak hours, this demonstrates the efficacy of the solar ventilation system in diminishing the buildup of volatile organic compounds, hence enhancing air quality and safety within the vehicle cabin.

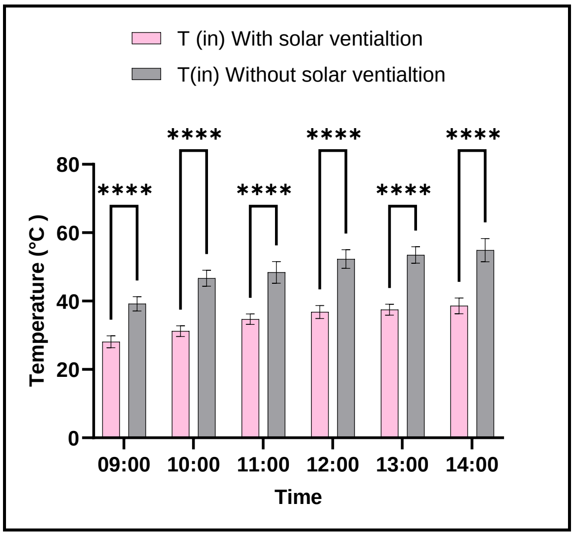

Figure 25. Statistical analysis between internal temperatures-with/without solar ventilation. Data represents three technical replicates. These data shown are mean value ±SD (p-value ****P ≤ 0.0001)

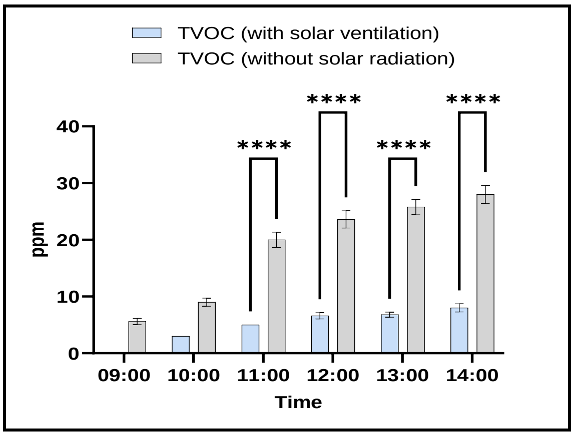

Figure 26. Statistical analysis between TVOC concentrations-with/without solar ventilation. Data represents three technical replicates. These data shown are mean value ±SD (p-value ****P ≤ 0.0001).

The air quality inside car cabins significantly affects the comfort, safety, and health of drivers and passengers. Research and daily experience highlight poor indoor air quality (IAQ) as a major issue in many vehicles. The World Health Organization identifies the high levels of volatile organic compounds (VOCs) and other pollutants in car air as a serious health risk. Table 4 summarizes related studies from different countries, outlining their locations and key findings. It highlights the greenhouse impact on VOC levels and cabin temperature, providing insight into the proposed system's performance. Variations in results are mainly influenced by experimental location, solar radiation intensity, and climate conditions.

4. Conclusion

This study compared experimental outcomes from two identical vehicles exposed to prolonged sunlight one equipped with a solar-powered ventilation system and the other without. Results indicated that the car with solar ventilation had, on average, a 30% lower cabin temperature. The non-ventilated vehicle reached a peak temperature of 59.2°C, while the ventilated vehicle peaked at 41.7°C, with an average temperature difference of 15.5°C. Additionally, the non-ventilated car recorded a maximum TVOC concentration of 30 ppm, compared to 9 ppm in the ventilated car. On average, TVOC levels were 3.1 times higher in the car without solar ventilation. These findings demonstrate the effectiveness of solar ventilation systems in reducing in-cabin heat and volatile organic compound (VOC) concentrations, contributing to enhanced thermal comfort, improved air quality, and reduced health risks for passengers. Furthermore, by decreasing the need for air conditioning, these systems can indirectly lead to lower fuel consumption and greenhouse gas emissions, supporting environmental sustainability in the transportation sector.

Based on the results of this study, several recommendations and directions for future research are proposed. Further improvement of solar ventilation technology is encouraged to enhance its efficiency, airflow capacity, and adaptability to different vehicle models. Integrating solar ventilation systems with smart environmental sensors and automated controls could optimize cabin air conditions dynamically. In addition, promoting public awareness and introducing regulatory guidelines for in-cabin air quality and ventilation standards are essential steps toward broader implementation. Future research should also include long-term field testing under various environmental conditions to assess durability and year-round effectiveness. Lastly, a comprehensive lifecycle and cost-benefit analysis of solar ventilation systems would support decision-making for manufacturers and policymakers aiming to adopt sustainable, health-conscious vehicle technologies.

Table 4. Summary of the reduction in the cabin temperature by using solar ventilation system and greenhouse impact on the VOC emission.

	Location	Main Result	Reference
Greenhouse effect on VOC emissions	Jordan	VOC emissions increase 3 to 6 times with higher temperatures.	Proposed system
	Poland	VOC emissions increase 3 to 36 times with higher temperatures.	[31]
	China	VOCs in closed car cabins at 20–25ºC can reach up to 8000 μg/m³.	[32]
	China	VOC emissions have been found to increase by 3 to 36 times with rising temperatures	[33]
	Sydney	new cars have shown TVOC levels as high as 64,000 μg/m³	[34]
	Switzerland	VOC emissions from a vehicle's interior can be up to 11 times higher at 50°C compared to 20°C.	[33]
	USA	The results showed that TVOC levels are 4 to 8 times higher when stationary than when driving	[13]
Cabin temperature reduction using a solar ventilation system	Jordan	30% lower temperature, with an average reduction of 15.5°C	Proposed system
	Malaysia	7 ºC air temperature reduction.	[35]
	Thailand	Replace car cabin hot air by ambient cold fresh air.	[36]
	Malaysia	The ventilated car reduced temperature by 25.33%.	[37]
	Oman	10 ºC average air temperature reduction.	[38]
	China	The equilibrium temperature is 12°C above the ambient temperature.	[39]
	China	5 to 10 °C cabin temperature more than ambient.	[40]
	UAE	4 °C average air temperature reduction.	[41]
	Korea	20% thermal comfort improvement.	[42]
	Malaysia	10 ºC average air temperature reduction.	[43]
	China	4.2 ºC average air temperature reduction.	[44]
	Malaysia	12% reduction in car cabin temperature.	[45]
	Malaysia	10 ºC air temperature reduction.	[46]

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