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Research Article

Effects of Car Air Freshener Formulations on Airborne Particle Concentrations in Solar-Heated Vehicle Cabins

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Abstract

Vehicle cabin air quality has become an important concern due to the accumulation of airborne pollutants in enclosed environments. In addition to emissions from interior materials, car air fresheners may influence airborne particle formation through the release and evaporation of fragrance-related volatile compounds, particularly under elevated temperatures caused by solar exposure. This study investigated the effects of different car air freshener types on vehicle cabin air quality through measurements of airborne particle concentrations and characterization of air freshener chemical compositions using Fourier Transform Infrared Spectroscopy (FTIR). Experiments were conducted using a Daihatsu Gran Max vehicle exposed to direct sunlight under four conditions: without air freshener, liquid air freshener, gel air freshener, and solid air freshener. Particle concentrations at six particle sizes (0.3, 0.5, 1.0, 2.5, 5.0, and 10.0 µm), cabin temperature, and relative humidity were recorded at 30-minute intervals over a three-hour period. The results showed that cabin temperature increased from approximately 24–28°C to more than 45°C during solar exposure, while relative humidity decreased substantially. The liquid air freshener produced the highest concentration of 0.3 µm particles, reaching 100,089 pcs/L, representing a 56.2% increase compared with the control condition. The gel air freshener increased particle concentration by 46.1%, whereas the solid air freshener exhibited the lowest particle levels throughout the experiment. FTIR analysis identified several volatile-related functional groups, including hydroxyl, aliphatic, ester, phosphate, nitro, and fluorinated compounds. The liquid and gel air fresheners exhibited a greater abundance of volatile-related functional groups, which corresponded to their higher airborne particle concentrations. These findings demonstrate that car air freshener formulation significantly influences airborne particle dynamics inside vehicle cabins under solar-heated conditions and suggest that low-volatility air freshener products may help reduce occupant exposure to airborne pollutants in tropical environments.

Keywords: Vehicle interior air quality; Car air freshener; Airborne particles; FTIR; Solar exposure; Particle concentration

The Technology Readiness Level (TRL) of this research is Level 3 (Proof of Concept). The proposed concept was successfully demonstrated through experimental measurements of airborne particle concentrations and FTIR characterization of different car air freshener formulations under realistic solar-heated vehicle cabin conditions. The findings provide initial scientific evidence of the influence of air freshener formulation on vehicle interior air quality. Further validation under diverse environmental conditions, multiple vehicle types, and long-term testing is required before advancing to higher TRL stages.

1. Introduction

Air quality is a key factor in determining human health, comfort, and safety. Over the past few decades, concerns about air pollution have focused primarily on the outdoor environment, particularly emissions from motor vehicles, industrial activities, and the combustion of fossil fuels [1], [2], [3], [4]. However, numerous studies have shown that microenvironments, such as vehicle cabins, can also be a significant source of human exposure to pollutants. Although time spent inside a vehicle is generally shorter than at home or work, concentrations of certain pollutants, including PM2.5, carbon monoxide (CO), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs), can be higher inside the vehicle cabin than in the outdoor environment. This is due to the contribution of vehicle interior materials, ventilation systems, and infiltration of pollutants from the surrounding environment [5], [6], [7], [8]. Exposure to these pollutants can increase health risks for drivers and passengers [9].

The vehicle cabin is an enclosed space with limited air volume and is composed of a variety of materials, including plastic, vinyl, rubber, textiles, adhesives, paints, and other composite materials [6], [10], [11]. These materials can release various volatile organic compounds (VOCs) through off-gassing. VOCs are a group of organic compounds that evaporate readily at room temperature and can accumulate in cabin air, especially under conditions of limited ventilation. Common VOCs detected in vehicle cabins include benzene, toluene, ethylbenzene, xylene, styrene, formaldehyde, and acetaldehyde [12], [13]. Short-term exposure to VOCs can cause irritation to the eyes, nose, and throat, as well as adverse effects on the nervous system, while long-term exposure can alleviate the growing concern about air quality inside vehicle cabins. This has led to increased attention being paid to the concept of Vehicle Interior Air Quality (VIAQ).

Many studies have shown that cabin air quality is influenced by various factors, including vehicle age [14], interior material characteristics [6], ventilation system [15], and cabin temperature [16], [17]. The concentration of pollutants inside a vehicle is also affected by traffic conditions [7], [8]. Among these factors, temperature is considered one of the most influential parameters because it directly affects the emission rate of volatile compounds from various sources inside the vehicle. When a vehicle is parked under direct sunlight, the cabin air temperature can increase substantially, while the surface temperature of the dashboard and other interior components can reach levels much higher than the ambient temperature [18], [19], [20]. These conditions accelerate the evaporation of organic compounds from interior materials, thereby increasing the potential for exposure to pollutants inside the cabin. Zhang et al. [16] reported that the surface temperature of materials is a key factor governing the distribution dynamics of VOCs inside the vehicle interior.

In addition to emissions originating from vehicle interior materials, pollutants within the cabin may also be emitted from products intentionally used by vehicle occupants, one of which is car air fresheners [21]. These products are widely used to enhance comfort by creating pleasant fragrances and eliminating unpleasant odors. From a psychological perspective, certain fragrances have been reported to provide positive effects on mood, reduce stress, improve comfort, and even influence driving performance [22], [23]. Consequently, the use of car air fresheners has become a common part of the everyday driving experience. Nevertheless, car air fresheners function by releasing volatile compounds into the cabin air. Steinemann et al. [21] reported that 12 car air freshener products analyzed emitted a total of 546 volatile compounds, of which 30 were classified as potentially hazardous to human health. The study also revealed that most of the detected compounds were not disclosed on product labels, leaving consumers unaware of the specific chemicals they are exposed to during air freshener use [24]. In addition to contributing to elevated concentrations of volatile compounds, emissions from air fresheners may also influence the formation of airborne particulate matter through processes such as evaporation, condensation, and the transformation of volatile compounds within enclosed environments [25].

Research in vehicle cabin air quality has evolved along several major directions, including the characterization of VOC emissions from interior materials, the modeling of pollutant distribution within vehicle cabins, the influence of temperature on volatile compound emissions, and health risk assessments associated with exposure to in-vehicle pollutants [10], [12], [13], [16], [26]. In contrast, studies on car air fresheners have primarily focused on psychological aspects, user comfort, and the effects of fragrances on driving behavior and performance [22], [23]. Meanwhile, investigations into the contribution of car air fresheners to vehicle cabin air quality remain relatively limited [21].

Although previous studies have substantially advanced the understanding of VOC emission mechanisms from vehicle interior materials and their associated health impacts, several important research gaps remain. First, most existing studies have focused on emissions originating from vehicle interior materials [5], [6], whereas the contribution of car air fresheners as a source of in-cabin pollutants has received relatively limited systematic investigation [21]. Second, research on car air fresheners has predominantly addressed aspects of user comfort, mood enhancement, and driving performance rather than their effects on cabin air quality [22], [23]. Third, studies integrating the use of car air fresheners with elevated cabin temperatures resulting from solar radiation exposure remain scarce, despite the fact that the influence of temperature on volatile compound emissions from both interior materials and air fresheners has been reported separately [13], [16], [21]. Finally, the relationship between volatile compound emissions from car air fresheners and changes in particulate matter concentrations within vehicle cabins is still not comprehensively understood [25].

To address this gap, this study provides new insights through an integrated investigation of the effects of different types of car air fresheners on airborne particle dynamics inside a vehicle cabin exposed to solar heating. Unlike previous studies, which typically evaluate vehicle interior materials or air freshener characteristics separately, this study integrates particle concentration analysis, cabin thermal condition monitoring, and chemical characterization of car air fresheners using Fourier Transform Infrared Spectroscopy (FTIR) to provide a more comprehensive understanding of potential pollutant exposure under realistic vehicle usage conditions. Therefore, this study aims to analyze the effects of different types of car air fresheners on air quality inside a vehicle cabin exposed to high temperatures due to solar radiation. Specifically, this study evaluates changes in airborne particle concentrations across various particle size fractions, examines the relationship between cabin temperature and particle dynamics, and identifies chemical characteristics of car air fresheners that may contribute to particle formation within the enclosed vehicle cabin environment.

2. Methods

2.1. Experimental design

An experimental study was conducted to simulate real-world conditions often encountered in tropical regions, where vehicles are typically parked in direct sunlight for extended periods. Under such conditions, high cabin temperatures can accelerate the release of volatile compounds from in-vehicle consumer products, including car air fresheners. Therefore, this study compared the dynamics of particulate matter concentrations under four cabin conditions: a control condition without air freshener and three commonly used air freshener formulations: liquid, gel, and solid. The experimental procedure consisted of cabin preparation through a flushing process, installation of measurement instruments, placement of the car air freshener, exposure of the vehicle to direct sunlight, measurement of airborne particulate matter concentration and in-cabin environmental parameters, and chemical characterization of the air freshener using FTIR, as presented in **Figure 1**.

The test vehicle used was a 2015 Daihatsu Gran Max Pick-Up equipped with a 1,495 cc gasoline engine and a standard factory-installed air conditioning system. This vehicle was chosen because it represents a common vehicle type in Indonesia and has a cabin volume that is easily controlled during the experimental testing. The vehicle specifications used in this study are presented in **Table 1**. The selected vehicles have not undergone any interior modifications and are maintained in normal operating conditions. The interior cabin materials, ventilation system, and seating configuration are maintained in their original condition throughout the experiment to minimize variability related to cabin characteristics.

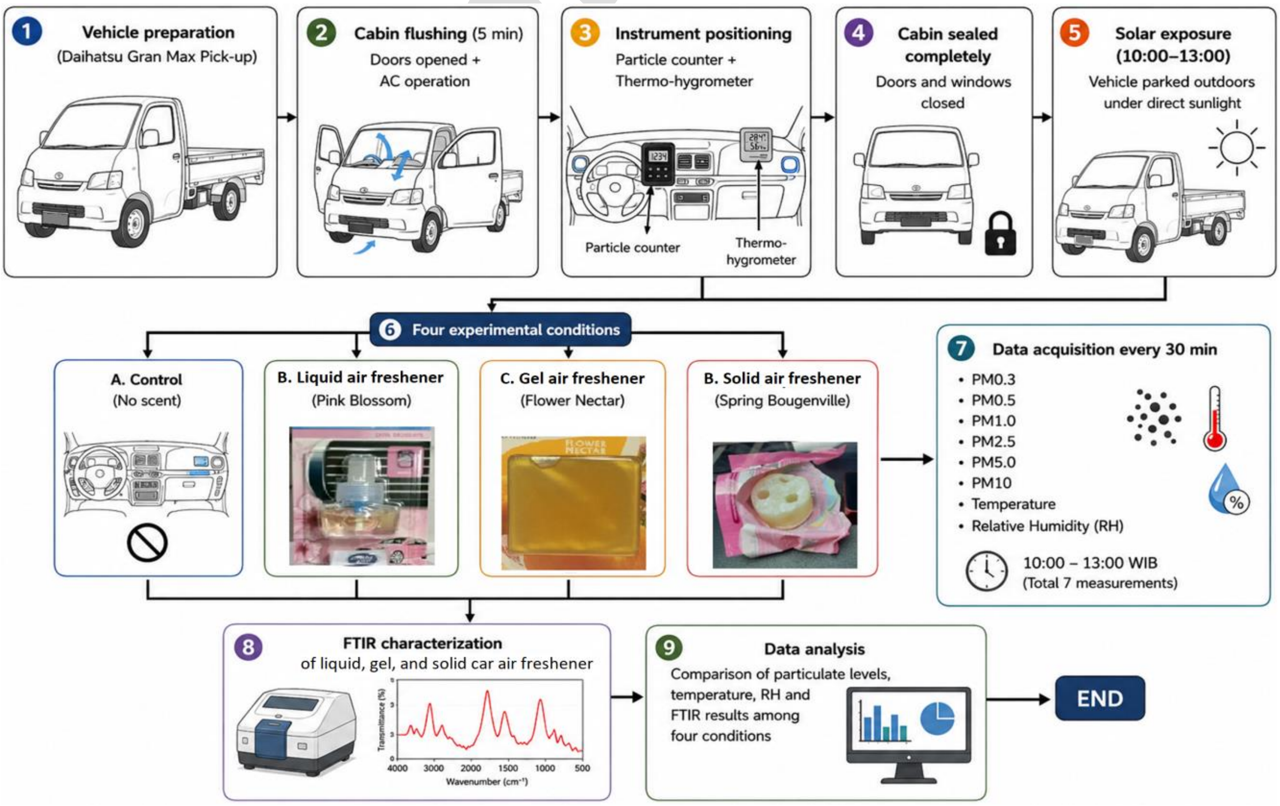


Figure 1. Schematic illustration of the experimental procedure for evaluating the effect of car air fresheners on vehicle cabin air quality

Table 1. Car Specifications

Parameter	Specification
Vehicle Model	Pick-up
Engine Type	1.5 L 3SZ-VE
Engine Displacement	1,495 cc
Fuel Type	Gasoline
Air Conditioning System	Available
Seat Material	Synthetic upholstery
Model Year	2015

All experiments were conducted in an open parking area at Campus 2 of Universitas Muhammadiyah Magelang (link to location), which received direct solar radiation throughout the testing period. The vehicle was parked with the engine turned off, and all doors and windows fully closed to simulate typical parked-vehicle conditions. During each experiment, airborne particulate concentrations and environmental parameters inside the cabin, including temperature and relative humidity, were continuously monitored. The collected data were subsequently analyzed to evaluate the effects of car air freshener use on vehicle cabin air quality. In addition, FTIR analysis was performed to identify the chemical characteristics of the compounds present in each air freshener formulation tested.

2.2. Materials and instruments

Airborne particle concentrations were measured using a laser-based particle counter capable of detecting particles with aerodynamic diameters of 0.3, 0.5, 1.0, 2.5, 5.0, and 10.0 µm. This instrument reports the number of particles per liter (pcs/L) and provides real-time measurements suitable for indoor air quality assessment. Prior to the experiments, a functional response check was conducted by exposing the particle counter to normal indoor air (low-particle condition) and cigarette smoke (high-particle condition). The objective was not to calibrate the instrument but to confirm its ability to respond consistently to substantial changes in airborne particle concentrations. As shown in **Figure 2a** and **Figure 2b**, the instrument exhibited a clear increase in particle counts under cigarette smoke exposure, indicating proper sensor functionality before the experimental measurements.

Three commercially available floral-scented car air fresheners, representing the most common consumer product formulations, were selected for this study: a liquid air freshener (Pink Blossom), a gel air freshener (Flower Nectar), and a solid air freshener (Spring Bougainvillea). These formulations were chosen to investigate how different fragrance release mechanisms affect airborne particulate dynamics within the vehicle cabin. The composition and characteristics of the products tested are summarized in **Table 2**. During each experiment, a single air freshener was placed in the center of the dashboard to maintain a consistent position relative to the monitoring instruments. All products were tested in their original commercial packaging and were freshly opened immediately before each experiment to minimize the influence of prior evaporation.

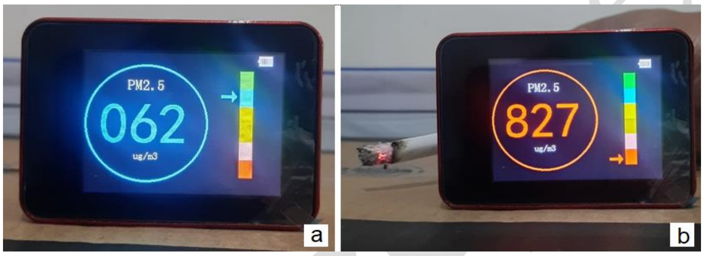


Figure 2. Preliminary verification of the particle counter: (a) measurement under normal indoor conditions and (b) measurement under cigarette smoke exposure

Table 2. Chemical composition of the car air fresheners

Composition	Liquid Air Freshener	Gel Air Freshener	Solid Air Freshener
Fragrance content	50%	90%	24%
Ethanol	n/a	Not specified on the product label	56%
Solvent	49%	n/a	n/a

2.3. Experimental procedure

Before each experiment, an initial conditioning procedure (flushing) was performed by opening all vehicle doors and operating the air-conditioning system for 5 minutes. This procedure was intended to minimize the influence of residual pollutants from previous tests and to establish comparable initial cabin conditions. The flushing process is illustrated in **Figure 3**.

After the flushing process, the particle counter and thermo-hygrometer was positioned on the vehicle dashboard, while the temperature and humidity sensor was placed in the central area of the cabin to provide a more representative measurement of the cabin air conditions. The instrument placement is shown in **Figure 4**.

Figure 3. Cabin flushing procedure prior to each experiment

Figure 4. Experimental conditions: (a) control without air freshener, (b) liquid air freshener, (c) gel air freshener, and (d) solid air freshener

Subsequently, all doors and windows were tightly closed, and the vehicle was locked to prevent disturbances during the experiment.

The experiments were conducted over four consecutive days, with one experimental condition evaluated each day. All tests were performed under comparable clear-sky weather conditions and direct solar exposure to promote cabin heat accumulation while minimizing environmental variability. The experimental conditions consisted of (a) a control without an air freshener, (b) a liquid air freshener (Pink Blossom), (c) a gel air freshener (Flower Nectar), and (d) a solid air freshener (Spring Bougainvillea), as illustrated in **Figure 4**.

For each experimental condition, data collection was conducted from 10:00 a.m. to 1:00 p.m. (WIB) at 30-minute intervals. This measurement period was selected because previous studies have reported that cabin temperature increases rapidly during late morning and reaches elevated levels around midday under tropical solar exposure conditions [18], [19], [20]. The monitored parameters included particle number concentrations at six particle sizes (0.3, 0.5, 1.0, 2.5, 5.0, and 10.0 μm), cabin temperature, and relative humidity. All observations were performed from outside the vehicle without opening the doors or windows, thereby maintaining stable cabin air conditions throughout the experiment.The study was designed as a comparative field experiment intended to represent practical vehicle-use conditions. Accordingly, environmental parameters such as solar radiation intensity and ambient weather conditions were not artificially controlled but were monitored throughout the experimental period.

2.4. FTIR analysis

In addition to particulate measurements, the chemical characteristics of the three car air freshener formulations were analyzed using Fourier Transform Infrared Spectroscopy (FTIR). The analysis was performed using a Compact FT-IR Spectrometer Alpha II (Bruker, Germany). FTIR was employed to identify the major functional groups present in each formulation and to provide qualitative information regarding chemical constituents that may contribute to the release of volatile organic compounds (VOCs) during evaporation. The obtained spectra were interpreted by comparing the major absorption bands with established functional group assignments and spectral library references. The FTIR results were subsequently used to support the interpretation of differences in airborne particle concentrations observed among the tested air freshener formulations.

2.5. Data analysis

Particle concentration data were analyzed descriptively to evaluate temporal variations under each experimental condition. The maximum particle concentrations and percentage changes relative to the control condition were calculated to compare the effects of the different air freshener formulations. Temperature and relative humidity data were examined to evaluate their temporal relationship with airborne particle concentrations during solar exposure. FTIR spectra were interpreted qualitatively to identify the dominant functional groups and were subsequently used to support the discussion of potential VOC emissions and their relationship with airborne particle dynamics.

3. Results and Discussion

3.1. Effect of cabin temperature on particle concentration

Thermal conditions inside the vehicle cabin changed substantially during sun exposure, as shown in **Figure 5**. Regardless of the air freshener formulation, cabin temperature continued to increase throughout the experiment, while relative humidity showed the opposite trend. Initial cabin temperature ranged from approximately 24–28°C and increased to 44–50°C after three hours of direct sunlight exposure. During the same period, relative humidity decreased from approximately 44–82% to 32–40%. These results indicate significant thermal accumulation inside the enclosed vehicle cabin under tropical solar radiation conditions. The observed temperature increase is consistent with previous studies investigating the thermal behavior of parked vehicles. Vishweshwara et al. [18] reported that cabin temperatures in vehicles exposed to direct sunlight can exceed 50°C under hot climate conditions. Similar observations were reported by Othoman et al. [19] and Chaurasiya et al. [20], who also documented substantial temperature increases in enclosed vehicle cabins exposed to solar radiation. Therefore, the thermal conditions observed in this study represent realistic operating conditions commonly encountered in tropical regions such as Indonesia.

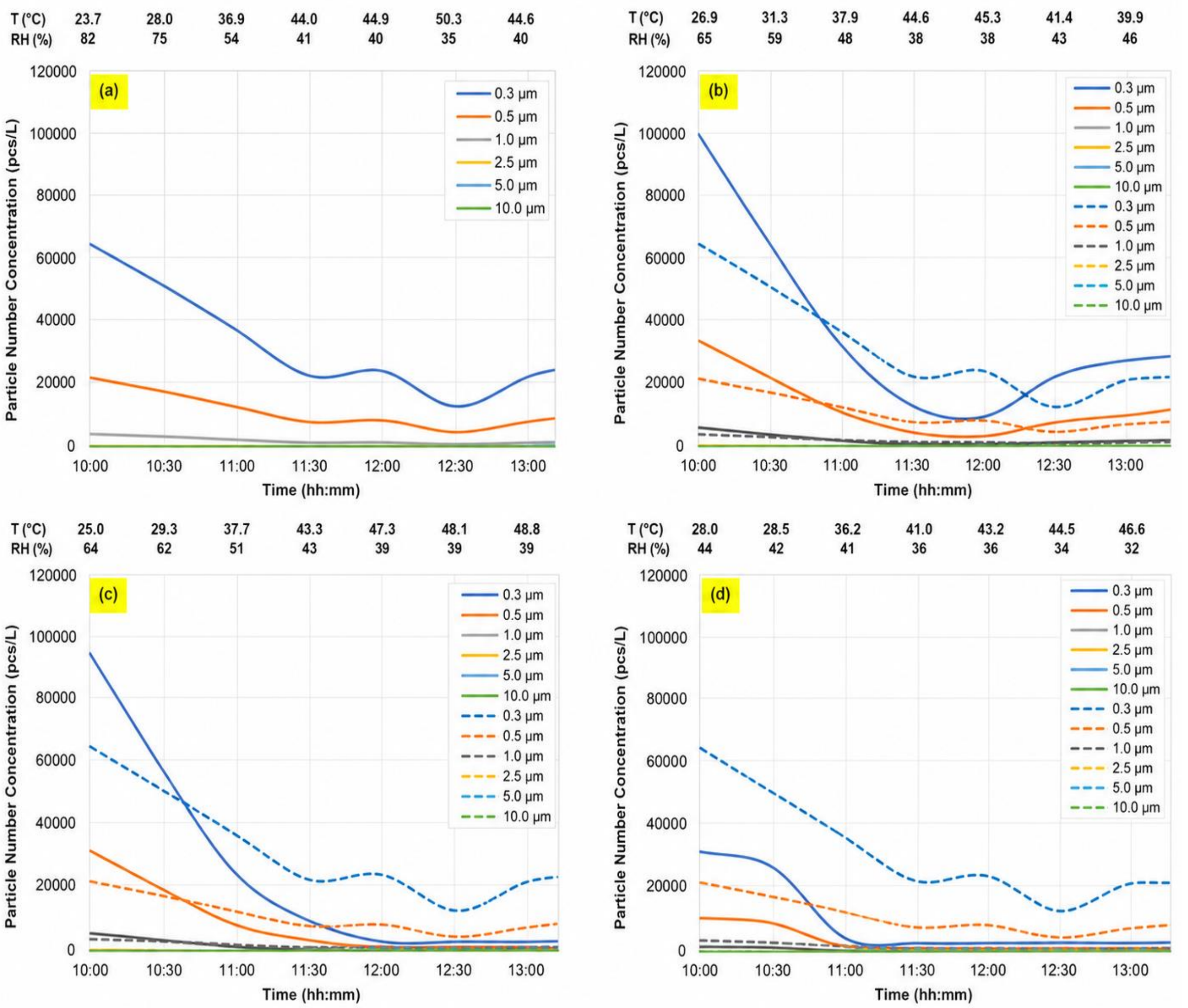


Figure 5. Temporal variation of particle concentrations inside the vehicle cabin under different air freshener conditions: (a) without air freshener, (b) liquid air freshener, (c) gel air freshener, and (d) solid air freshener

High cabin temperature is recognized as a major factor affecting vehicle interior air quality because it accelerates the evaporation of volatile compounds released from interior materials and consumer products. Previous studies by Wang et al. [13], Huang et al. [14], and Zhang et al. [16] showed that increasing temperature significantly increases the evaporation of organic compounds from vehicle interior materials. Zhang et al. [16] further reported that material surface temperature significantly influences the emission dynamics and distribution of volatile compounds within a closed vehicle cabin. Therefore, the high temperatures observed in this study are expected to increase the evaporation of volatile compounds associated with the fragrances of the tested air fresheners. Because the release of volatile compounds can influence the formation of airborne particles through evaporation, condensation, and nucleation processes, the temporal variation of particle concentrations was then examined. The temporal variation of particle concentrations under the four experimental conditions is presented in **Figure 5**. In all cases, particles with a diameter of 0.3 μm represented the dominant submicron particle fraction, while larger particles (≥2.5 μm) were detected at much lower concentrations. This finding indicates that submicron particles constituted the major fraction of particles in the air inside the vehicle cabin during the experiments.

Although high temperatures are expected to increase the release of volatile compounds, particle concentrations generally decreased over time. For example, under control conditions, the concentration of 0.3 μm particles decreased from 64,072 pcs/L at the beginning of the experiment to 12,424 pcs/L after 2.5 hours of sunlight exposure before increasing slightly at the final measurement. Similar temporal trends were observed for other particle size fractions and air freshener formulations. These observations suggest that the measured particle concentrations are governed by the balance between particle formation and particle removal processes occurring within the enclosed cabin environment. As the experiment progressed, removal mechanisms such as gravitational settling, particle coagulation, and deposition on interior surfaces gradually became more dominant, resulting in a net reduction in airborne particle concentrations. These findings indicate that the vehicle cabin microenvironment is highly dynamic under sunlight exposure. While elevated temperatures can enhance the evaporation of volatile compounds associated with fragrances, the resulting particle concentrations are simultaneously influenced by competing physical removal processes. Consequently, the measured airborne particle concentrations reflect the combined effects of particle formation and removal, not just emission processes alone. The influence of various air freshener formulations on these particle dynamics is discussed in the next section.

3.2. Influence of car air freshener type on cabin particle concentration

The influence of air freshener formulation on airborne particle concentration is presented in **Figure 5**. Significant differences were observed among the tested air freshener types, particularly for particles with a diameter of 0.3 μm, which represented the dominant particle fraction under all experimental conditions. Among the tested products, the liquid air freshener generated the highest particle concentration, followed by the gel air freshener, the control condition, and the solid air freshener. These results indicate that air freshener formulation plays an important role in determining airborne particle dynamics inside solar-heated vehicle cabins. **Table 3** summarizes the maximum particle concentrations observed during the experiments. The liquid air freshener produced a peak concentration of 100,089 pcs/L for 0.3 μm particles, corresponding to a 56.2% increase relative to the control condition. The gel air freshener exhibited a maximum concentration of 93,614 pcs/L, representing a 46.1% increase compared with the control. In contrast, the solid air freshener generated substantially lower particle concentrations, with a maximum value of 31,333 pcs/L, approximately 51.1% lower than the control condition. As summarized in **Table 3**, the liquid air freshener produced the highest concentration of 0.3 μm particles, reaching 100,089 pcs/L, which was 56.2% higher than the control condition. The gel air freshener also increased particle concentration by 46.1%, whereas the solid air freshener exhibited substantially lower concentrations than the control condition. These results indicate that air freshener formulation plays an important role in determining airborne particle concentrations inside solar-heated vehicle cabins.

Table 3. Maximum concentration of 0.3 μm particles under different experimental conditions

Condition	Maximum 0.3 μm Particle Concentration (pcs/L)	Change Relative to Control (%)
Control	64,072	–
Liquid Air Freshener	100,089	+56.2
Gel Air Freshener	93,614	+46.1
Solid Air Freshener	31,333	−51.1

The liquid air freshener exhibited the strongest effect on airborne particle generation throughout the exposure period. The highest particle concentrations were observed during the early stages of solar exposure when cabin temperature increased rapidly. This behavior may be attributed to the presence of solvent components that facilitate rapid evaporation under elevated temperatures. Liquid formulations generally provide minimal resistance to mass transfer, allowing fragrance-related compounds to be released more readily into the cabin environment. This observation is consistent with the findings of Steinemann et al. Steinemann et al. [21], who reported that commercial car air fresheners release hundreds of volatile compounds, many of which possess high volatility and can be emitted rapidly in enclosed environments. Under elevated cabin temperatures, these compounds are expected to evaporate more efficiently, thereby increasing the likelihood of airborne particle formation through condensation and nucleation processes.

The gel air freshener also produced considerably higher particle concentrations than the control condition, although its maximum concentration remained lower than that of the liquid air freshener. Interestingly, the product information indicated that the gel air freshener contained a higher fragrance proportion than the liquid air freshener. Nevertheless, the measured particle concentration was lower. This finding suggests that fragrance content alone does not determine pollutant generation inside vehicle cabins. Instead, the physical form of the air freshener appears to play a significant role. The gel matrix likely acts as a diffusion barrier that restricts the release of volatile compounds, resulting in a slower evaporation rate compared with liquid formulations. Consequently, particle generation is influenced not only by chemical composition but also by mass transfer characteristics and release mechanisms.

Among all tested products, the solid air freshener exhibited the lowest particle concentrations throughout the experiment. The maximum concentration of 0.3 μm particles was substantially lower than both the liquid and gel air fresheners and even lower than the control condition. This result indicates that the solid matrix significantly limited the release of volatile compounds under elevated temperatures. The reduced particle concentration may be attributed to the low volatility and diffusion-controlled release mechanism of the solid formulation. Unlike liquid and gel products, fragrance compounds embedded within a solid carrier require a longer time to migrate to the surface before evaporation can occur. As a result, the formation of airborne particles was considerably suppressed during the experimental period.

These findings demonstrate that air freshener formulation is a critical factor influencing airborne particle concentrations inside vehicle cabins. Similar observations were reported by Lee et al. [25], who found that air freshener use inside vehicles increased both particulate concentrations and volatile compound levels. The present study extends these findings by demonstrating that elevated temperatures caused by solar exposure may further amplify the effects of air freshener products on cabin air quality. Furthermore, the results support previous studies emphasizing the importance of temperature-driven volatilization processes in enclosed vehicle environments [13] [16]. While previous investigations primarily focused on emissions from interior materials, the present findings indicate that air freshener products can also represent a meaningful source of airborne pollutants under realistic solar-heated conditions.

3.3. Relationship between temperature, humidity, and particle dynamics

The relationships among cabin temperature, relative humidity, and airborne particle concentration are presented in **Figure 6**. During the three-hour solar exposure period, cabin temperature increased continuously while relative humidity decreased substantially. In contrast, airborne particle concentrations generally exhibited a declining trend after reaching their initial peak values. This observation indicates that particle dynamics inside the vehicle cabin were governed by a complex interaction between thermal conditions and particle removal processes. The inverse relationship between temperature and relative humidity observed in this study is consistent with previous investigations of solar-heated vehicle cabins. Othoman et al. [19] reported that increasing cabin temperature under solar exposure is commonly accompanied by a reduction in relative humidity because warmer air can retain larger quantities of water vapor. Similar thermal behavior has also been reported by Vishweshwara et al. [18] and Chaurasiya et al. [20] for parked vehicles exposed to direct sunlight.

As cabin temperature increased, the evaporation of fragrance-related compounds and other volatile substances present inside the cabin was expected to become more intensive. Previous studies by Wang et al. [13], Huang et al. [14] and Zhang et al. [16] demonstrated that temperature is one of the most important factors controlling the release of volatile compounds from vehicle interior materials. Elevated temperatures increase molecular activity and vapor

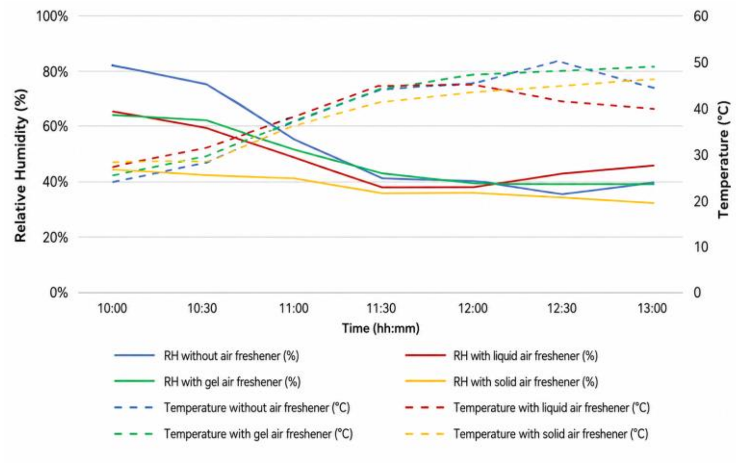


Figure 6. Variation of cabin temperature and relative humidity during solar exposure under different air freshener conditions.

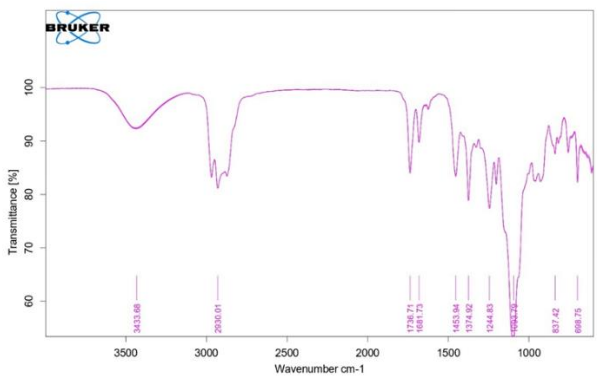
pressure, thereby accelerating volatilization processes. Consequently, the increasing temperature observed in the present study likely enhanced the release of volatile compounds from the tested air freshener products. However, despite the potential increase in volatile compound release, airborne particle concentrations did not continue to increase throughout the experiment. Instead, particle concentrations gradually declined after the initial measurement period.

The observed decline in particle concentration despite continuously increasing temperature suggests that particle removal mechanisms eventually became dominant over particle generation processes. During the early stages of solar exposure, rapid evaporation of fragrance compounds may have contributed to particle formation, resulting in elevated concentrations. As exposure continued, airborne particles were progressively removed through gravitational settling, coagulation, and deposition onto cabin surfaces such as seats, dashboard components, windows, and interior trim materials. Particle coagulation may also have contributed to the reduction of ultrafine particle concentrations. Small particles tend to collide and combine to form larger particles, thereby decreasing the total particle number concentration measured by the particle counter. In addition, deposition rates generally increase with exposure time because particles continuously interact with cabin surfaces within the confined environment.

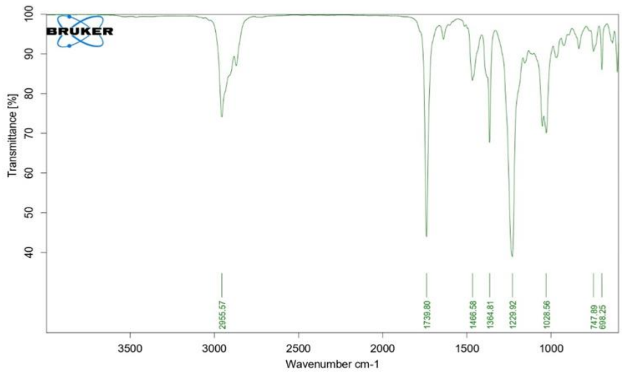
The results indicate that vehicle cabin air quality is influenced not only by pollutant emission sources but also by the balance between emission and removal mechanisms. Similar conclusions were highlighted in reviews by Xu et al. [5] and Badawy and Hashem [6], which identified temperature, ventilation conditions, and pollutant transport processes as major factors affecting vehicle interior air quality. Therefore, particle concentrations observed inside the cabin should be interpreted as the net outcome of simultaneous generation, transport, coagulation, and deposition processes. From an exposure perspective, the results suggest that the highest occupant exposure to airborne particles may occur during the early stages of cabin heating when volatile compounds are released rapidly and particle concentrations remain elevated. Although particle concentrations tended to decrease over time, the initial exposure period may represent a critical condition for vehicle occupants entering a cabin that has been parked under direct sunlight. These findings emphasize the importance of ventilation and cabin cooling strategies before vehicle use, particularly in tropical climates where cabin temperatures frequently exceed 45°C.

3.4. FTIR characterization of car air fresheners

To better understand the differences in airborne particle concentrations observed among the tested air freshener formulations, Fourier Transform Infrared Spectroscopy (FTIR) analysis was performed to identify the major functional groups present in each product. The FTIR spectra of the liquid, gel, and solid air fresheners are presented in **Figure 7**, while the major absorption bands and corresponding functional group assignments are summarized in **Table 4**. The identified functional groups provide valuable information regarding the chemical characteristics of the tested products and may help explain differences in their behavior under elevated cabin temperatures. The FTIR spectrum of the liquid air freshener exhibited several prominent absorption bands associated with hydroxyl (O–H), aliphatic C–H, ester (C=O), amide, carboxylate, and fluorinated functional groups. These functional groups are commonly found in fragrance formulations, solvents, and performance-enhancing additives used in commercial air fresheners. The presence of ester and aliphatic groups indicates the existence of organic compounds that can readily interact with the surrounding environment during the evaporation process. Combined with the particle concentration measurements, these results suggest that the liquid formulation allowed fragrance-related compounds to be released more readily into the cabin environment, which may have contributed to the higher particle concentrations observed during the experiments.



(a)



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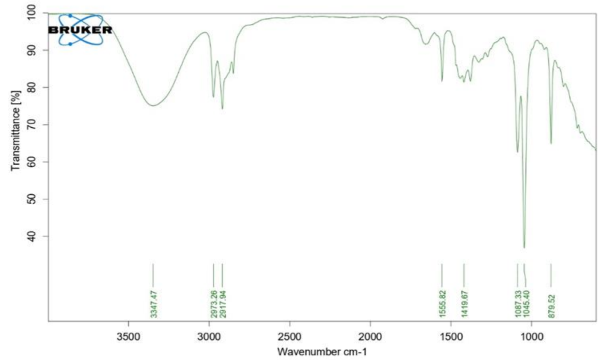

(c)

Figure 7. FTIR spectra of the tested car air fresheners: (a) liquid air freshener (Pink Blossom), (b) gel air freshener (Flower Nectar), and (c) solid air freshener (Spring Bougenville)

Table 4. Major FTIR absorption bands identified in the tested air fresheners

Air freshener Type	Peak (cm^{-1})	Functional Group Assignment
Liquid	3433.68	O–H stretching
Liquid	2930.01	Aliphatic C–H
Liquid	1736.71	Ester (R–C–OR)
Liquid	1681.73	Amide
Liquid	1374.92	Carboxylate
Liquid	1093.79	C–F stretching
Gel	2955.50	Aliphatic C–H
Gel	1739.80	Ester (R–C–OR)
Gel	1229.92	Aromatic phosphate
Gel	1028.56	Aliphatic phosphate
Solid	3347.47	O–H stretching
Solid	2973.26	Aliphatic C–H
Solid	1555.82	Nitro compound
Solid	1045.40	C–F stretching
Solid	1419.67	Carbonate compound

The gel air freshener exhibited functional groups similar to those identified in the liquid formulation, including aliphatic, ester, and phosphate-related compounds. Library matching analysis indicated similarity with several fragrance-related compounds commonly used in commercial products. Although the gel air freshener contained a high fragrance content according to the product label, its particle concentrations remained lower than those obser ved for the liquid formulation. This finding suggests that chemical composition alone does not determine airborne particle concentrations. The gel matrix likely acted as a physical barrier that moderated the release of fragrance compounds, resulting in a slower transfer of volatile components from the product into the cabin air.

The FTIR spectrum of the solid air freshener also revealed several functional groups associated with fragrance ingredients, including hydroxyl, aliphatic, nitro, carbonate, and fluorinated compounds. However, the solid formulation produced substantially lower particle concentrations than both the liquid and gel products. This behavior is likely related to the physical structure of the solid matrix, which restricts the movement of fragrance compounds and limits their release into the surrounding air. As a result, the transfer of fragrance-related compounds from the product to the cabin environment may occur more gradually than in liquid or gel formulations.

The FTIR results indicate that the three air fresheners possessed distinct chemical characteristics despite sharing several common fragrance-related functional groups. When considered together with the particulate measurements, the findings suggest that both chemical composition and physical formulation influence the release behavior of fragrance compounds under solar-heated cabin conditions. The liquid formulation exhibited the greatest impact on airborne particle concentrations, whereas the solid formulation showed the lowest impact throughout the exposure period. These results highlight the importance of considering not only fragrance composition but also product formulation when evaluating the potential influence of air fresheners on vehicle cabin air quality. It should be noted that FTIR analysis provides information on functional groups rather than direct identification of individual chemical species. Therefore, the compound assignments presented in this study are based on spectral interpretation and library matching results. More detailed characterization of fragrance emissions would require complementary analytical techniques, such as gas chromatography–mass spectrometry (GC–MS). Nevertheless, FTIR remains a useful tool for comparing the chemical characteristics of different air freshener formulations and supporting the interpretation of their observed effects on airborne particle concentrations

3.5. Implications for vehicle interior air quality

Vehicle interior air quality (VIAQ) is receiving increasing attention because pollutants can accumulate inside enclosed vehicle cabins. Previous studies have primarily focused on VOC emissions from interior materials such as plastics, textiles, adhesives, and dashboard components [5], [6], [10], [12]. This study shows that, in addition to these emission sources, commercially available car air fresheners can also impact cabin air quality. Significant differences in airborne particle concentrations were observed among the tested air freshener formulations, suggesting that product formulation plays a significant role in determining occupant exposure under solar heating conditions.

Among the tested products, liquid and gel air fresheners produced significantly higher concentrations of 0.3 μm particles than the control condition, while solid air fresheners consistently showed the lowest concentrations. These findings suggest that airborne particle concentrations are influenced not only by the product's chemical composition but also by its physical formulation, which governs the release characteristics of fragrance-related compounds. This interpretation is supported by FTIR results and is consistent with previous studies reporting that commercial car air fresheners can emit volatile compounds and increase air pollutant levels inside vehicle cabins [21], [25].

Although airborne VOC concentrations were not directly measured, the increased concentrations of submicron particles observed in this study may contribute to increased passenger exposure, particularly when entering vehicles that have been parked in direct sunlight without prior ventilation [1]. Future research should combine direct VOC measurements using GC–MS and repeated experiments under controlled environmental conditions to better understand the relationship between air freshener formulation, VOC emissions, airborne particle concentrations, and vehicle interior air quality.

4. Conclusion

This study evaluated the influence of different car air freshener formulations on airborne particle concentrations inside a solar-heated vehicle cabin. Solar exposure caused substantial thermal accumulation, increasing cabin temperatures to above 50°C while reducing relative humidity, conditions that may enhance the release of fragrance-related compounds. Among the tested products, the liquid air freshener produced the highest concentration of 0.3 μm particles, followed by the gel air freshener, whereas the solid air freshener consistently exhibited the lowest particle concentrations. FTIR analysis further indicated that differences in both chemical characteristics and physical formulation contributed to the observed particle behavior. The results demonstrate that car air freshener formulation is an important factor influencing vehicle interior air quality under elevated temperature conditions. Solid air fresheners may therefore represent a preferable alternative for reducing airborne particle exposure in hot climates. Future studies should incorporate direct VOC measurements and replicated experiments under controlled environmental conditions to further clarify the relationship between air freshener formulation, thermal exposure, and airborne particle dynamics.

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