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Research Paper

The smoking of heat-not-burn (HNB) cigarette products and its effects on indoor air quality

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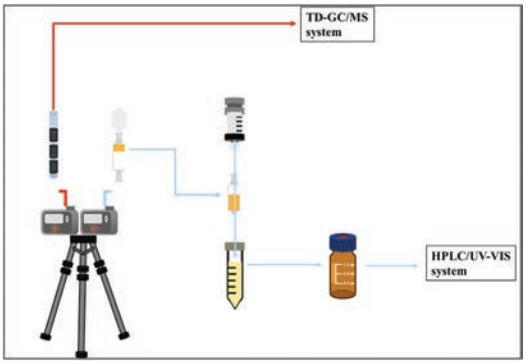
HIGHLIGHTS

- The emission concentrations of VOCs and CCs from HNB smoking are monitored.
- Their TVOC concentrations are compared under different smoking/ventilation conditions.
- The VOC levels by HNB smoking is about an order of magnitude lower than those of 1R6F.
- VOC pollution by HNB smoking is also analyzed in reference to cooking activities.
- Health risks of key VOCs are assessed using HQ and ILCR metrics under realistic exposure scenarios.

GRAPHICAL ABSTRACT



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ABSTRACT

In this research, the concentration levels of volatile organic compounds (VOCs) are monitored in a designated smoking booth using heat-not-burn (HNB) cigarettes (in reference to 1R6F cigarette) with controlled variables of number of cigarettes smoked (1, 3, and 6 cigarettes), booth ventilation (closed vs. open), and time after the release of cigarette smoke ($T_0 = 0$, $T_1 = 5$, $T_2 = 10$, and $T_3 = 20$ min)). The total VOC concentration (TVOC) released from an HNB cigarette is compared as a collective group (TV_{all}) and as three individual subgroups (TV_n: TV_1 for 14 standardized VOCs (G_1), TV_2 for 17 reference VOCs (G_2), and TV_3 for 10 carbonyl compounds (CCs: G_3). Comparative analysis of TVOC emission concentration levels is performed in closed/open booth conditions. Accordingly, TVOC concentrations from HNB (1347/416 ppbC) are about one order of magnitude lower than those from 1R6F (14834/3435 ppbC). Nonetheless, the predominant components in $G_1/G_2/G_3$ of HNB are clearly identified as isoprene (14.2 ppb), dodecane (16.8 ppb), and acetaldehyde (17.6 ppb), respectively. The VOC emission characteristics of HNB cigarettes are further evaluated against conventional cigarettes (i.e., 1R6F) and typical indoor cooking activities (data for the latter from a complementary experiment in this study). Overall, the results underscore the relative emission potential of different indoor sources, offering valuable insight into their comparative impact on indoor air quality.

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1. Introduction

Cigarette smoke is a prevalent public health concern due to its adverse health complications [36]. Cigarette smoke contributes to severe health issues such as heart attacks, chronic obstructive pulmonary disease, lung cancer, and emphysema [14,47]. In recent years, the utility of novel tobacco products such as heat-not-burn (HNB) cigarettes has gained attention as a potential alternative to traditional burning cigarettes [1]. The HNB is an electronic cigarette that heats (without combustion) tobacco-containing cigarettes to produce inhalable fumes for the user [10]. Over the past decade, there has been a remarkable surge in the global market share of HNB cigarettes [18]. As such, the consumption of HNB tobacco products has been growing rapidly, as HNBs are reported as potentially lower-risk alternatives to traditional combustible cigarettes [38].

The primary distinction between HNB and conventional burning cigarettes is the difference in temperature at which the product is being consumed. The former is typically heated to 250–350 °C, while the latter burns at much higher temperatures (800 °C) [44]. Because of this difference, each product can exhibit a distinct emission concentration profile of harmful components such as volatile organic compounds (VOCs) and carbonyl compounds (CCs) [42]. Notably, HNB devices can deliver an up to 83 % nicotine intake with noticeable reduction in the measured residual concentrations of potentially harmful constituents such as formaldehyde (FA, up to 80 %), acetaldehyde (up to 62 %), and particulate matter (up to 75 %) [2,44].

It has been demonstrated that HNB cigarette emissions contain not only gaseous compounds but also particulate matters (PM) and associated pollutants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and ultrafine particles [44]. For example, PM emissions from HNB devices have been reported to be approximately 75 % lower than those from conventional cigarettes, although trace amounts of metals (e.g., nickel and chromium) and PAHs are still detected in HNB aerosols [39]. In contrast, gaseous components like VOCs, particularly those with carbonyl functional groups (C═O) have emerged as dominant pollutants in HNB cigarette emissions with the potential health risks [1]. Specifically, a range of carbonyl-containing VOCs, especially those containing carbonyl functional groups (e.g., FA, acetaldehyde, acrolein, and propionaldehyde) have been identified in HNB smoke [12,31,51].

Given the environmental concerns associated with VOC emissions, the pollution caused by HNB cigarette smoking has been extensively studied in recent years. Such emissions from HNB devices are influenced by multiple factors, including device design, heating source, tobacco blend, puffing behavior, and environmental conditions [35]. To address the potential environmental impacts of HNB cigarette smoking, it is essential to establish a database on VOC concentrations and their relative compositions during consumption. This information will provide a clearer understanding of the associated risks, particularly in the context of indoor air quality [20,34].

With the introduction of designated smoking rooms for public use, people in these confined spaces are exposed to varying levels of hazardous VOCs and CCs (de [17]). However, limited efforts have been made to assess air quality in such environments. This study aims to evaluate the impact of HNB cigarette smoke in confined spaces, particularly designated smoking booths, through field measurements of VOC and CC emissions. Recent investigations have monitored detailed emission profiles from 1R6F cigarettes under controlled smoking conditions, including variations in the number of cigarettes smoked and ventilation settings (e.g., door closed vs. open for 30 min) [27]. Additionally, comparative measurements were conducted to assess pollution levels from other indoor activities such as cooking. Unlike earlier studies that focused on either limited compound categories or generic ventilation setups, this study integrates real-world exposure scenarios by varying the number of cigarettes, ventilation states, and time profiles in a standardized chamber system. This structure allows for improved reproducibility and comparison across both chemical and behavioral conditions. This research provides a comprehensive assessment of HNB smoking effects, offering valuable insights into its contribution to indoor air quality relative to those of common household activities.

2. Materials and methods

2.1. Materials

Totals of 14 VOCs and 10 CCs were selected as the target air pollutants for HNBs in reference to the International Organization for Standardization (ISO) [24,23] (Table S1). The 14 VOCs comprised 1, 3-butadiene (1,3-B), acrylonitrile (AN), isoprene (IP), methyl ethyl ketone (MEK), benzene (B), toluene (T), *p*-xylene (*p*-X), *m*-xylene (*m*-X), *o*-xylene (*o*-X), styrene (S), *o*-cresol (*o*-C), phenol (PHN), *p*-cresol (*p*-C), and *m*-cresol (*m*-C). The 10 CCs were formaldehyde (FA), acetaldehyde (AA), acrolein (ACR), acetone (ACT), propionaldehyde (PA), crotonaldehyde (CA), butyraldehyde (BA), benzaldehyde (BZA), isovalealdehyde (IA), and valeraldehyde (VA) (Table S1).

Reagent grade chemicals (RGCs) were purchased and used as primary standards (PSs) for the VOCs (1) 1,3-B and IP (Tokyo Chemical Industry, Japan), (2) AN, MEK, B, T, *p*-X, *o*-X, S, *o*-C, PHN, *p*-C, and *m*-C (Sigma Aldrich, USA), and (3) *m*-X (Yakuri Pure Chemicals, Japan). To prepare the PSs of the 10 CCs, a mixture of derivatization reagent (10 mL) was created using a concentrated 15 ng/μL 2,4-dinitrophenylhydrazine (DNPH) solution obtained from the TO11/IP-6A Aldehyde/Ketone-DNPH Mix (Sigma-Aldrich, USA). This solution was used for capturing and analyzing aldehydes and ketones in air samples. The 25 mL gas-tight syringes were purchased from SGE, Australia. The Carbopack C (40/60 mesh), Carbopack B (40/60 mesh), and Carbopack X (40/60 mesh) were purchased from Sigma-Aldrich (USA) for preparation of the three-bed adsorption tubes used for sample collection of VOCs and CCs. For the generation of HNB cigarette smoke, a hybrid of conventional and electronic cigarettes (an IQOS 3 DUO model A1406: Philip Morris International (PMI)) was used as the heating device. The HNB cigarettes utilized in this study were Heets Purple Wave procured from a local Korean market. These cigarettes feature a distinct purple color and are formulated from a tobacco blend infused with a blueberry flavor. The reference 1R6F cigarettes were obtained from the University of Kentucky's Center for Tobacco Reference Products (CTRP). Both types of cigarettes were used after being stored at 25 °C and 60% humidity for 48 h (Table S1). In addition to standard carbonyl compounds listed in ISO protocols, other target VOCs (e.g., benzene, toluene, styrene, and xylene isomers) were also selected based on their frequent detection in tobacco smoke or indoor environments, as reported in previous studies [2,31].

2.2. Preparation of working standards for quantitation of VOCs and CCs

To prepare the liquid working standard (WS) of 14 VOCs, a three-step dilution was performed using their RGCs as the PS in methanol (99.9 %, Sigma-Aldrich, St. Louis, USA) (Table S2 (a)). Considering differences in the conditions of the PS components (e.g., concentration levels, density, and phase type (liquid/solid)), four PSs were prepared: PS-A, PS-B, PS-C, and PS-D based on volatility, solubility, and physical state (liquid/solid), ensuring appropriate handling and dilution strategies for each group. (1) PS-A was comprised of 1,3-Bu. (2) PS-B was comprised of AN, IP, MEK, B, T, p-X, m-X, o-X, and S. (3) PS-C contained o-C and m-C. (4) PS-D was PHN and p-C. For PS-A, 1000 μL of 1,3-Bu was prepared and added to a 1 mL vial. In PS-B, 140 μL of each compound was mixed with 700 μL of methanol solution in a 2 mL vial. Similarly, for PS-C, 200 μL of each compound was added to 1400 mL of methanol in a 2 mL vial. PS-D was prepared by adding 400 mg of each compound in 20 mL of methanol.

Using these four types of PS, the WS-I and WS-II were prepared in a two-step procedure. In the first step, WS-I_a and WS-I_b were prepared. The WS-I_a was prepared by diluting 20 μL of PS-A in 2000 μL of

methanol. Similarly, the WS-I_b was prepared for all remaining VOCs by mixing 300 μL of PS-B, 200 μL PS-C, and 800 μL of PS-D into 18,700 μL of methanol.

The WS-II solutions were prepared at six concentration levels by gravimetrically diluting WS-I_a and WS-I_b simultaneously in methanol to produce a unified calibration mixture. As such, the average concentrations of the 14 VOCs for six-point calibration were (1) 6.18 ± 1.21, (2) 12.4 ± 2.43, (3) 30.9 ± 6.07, (4) 61.8 ± 12.1, (5) 124 ± 24.3, and (6) 247 ± 48.5 μg/mL. The calibration curve was produced by injecting 1 μL of each WS into an adsorption tube in preparation for gas chromatography-mass spectrometry (GC-MS). The calibration curves for VOCs and CCs were constructed using six-point serial dilutions of the working standards. All calibration curves showed strong linearity ($R^2 > 0.99$) within the calibrated concentration ranges, ensuring reliable quantification. For the G_2 VOC group, quantification was performed using the Compounds Lacking Authentic Standards or Surrogates (CLASS) approach reported previously [28]; it allows to estimate the response factors based on molecular structure–related parameters such as carbon number and polarity. Specifically, relative response factors were extrapolated by applying a linear regression model derived from the calibration data of G_1 VOCs, allowing for the estimation of concentrations of structurally similar G_2 compounds. The adsorption tube was purged with ultra-pure N_2 gas at 100 mL min^{-1} for 3 minutes using a vacuum pump (MP-Σ30NII, SIBATA, Japan) to remove moisture. Afterward, the quantitative analysis of VOCs collected on the adsorption tube was performed by thermal desorption (TD, Series 2 Unity, Markes International, UK)-GC (GC-2010 Plus, Shimadzu, Japan)-MS (GCMS-QP 2010 Ultra, Shimadzu, Japan).

The adsorption tube was prepared with three-bed sorbents by loading 50 mg each of Carbopack C, Carbopack B, and Carbopack X into a quartz tube system (length (9 mm), OD (6 mm), and ID (5 mm); Camsco, USA) plugged with quartz wool plugs at both sides. Prior to sampling of the VOCs, the adsorption tubes were thermally conditioned at 320 °C for 3 h under a continuous flow of ultra-pure N_2 (100 mL min^{-1}) using a tube conditioner (CT 2000 Tube Cleaner, Korea) to remove impurities and moisture on the adsorbent surface. After conditioning, the adsorption tube was sealed with a plastic cap and stored until use

For quantitative analysis of the CCs, the PS of the DNPH mix (15 ng μL^{-1}) was diluted in 99.9 % pure acetonitrile (Sigma Aldrich, USA). The initial working standard for CCs (hereafter referred to as WS (CC_i)) was prepared by diluting 400 μL of DNPH PS in 1600 μL of acetonitrile in a 2 mL vial. The final working standards (WS (CC_f)) were prepared by serial dilution of the WS (CC_i) into five concentration levels (0.15, 0.30, 0.75, 1.50, and 3.00 ng μL^{-1}) (Table S2 (b)). The WS (CC_f) were analyzed using high-performance liquid chromatography (HPLC) equipped with an ultraviolet (UV) detector to produce a five-point calibration curve.

2.3. Instrumental system for VOCs analysis

2.3.1. TD-GC-MS system

Analysis of the adsorption tubes containing the target VOCs was performed using a TD-GC-MS system as follows. Thermal desorption of the VOCs was induced at 320 °C for 5 min in an ultra-pure helium carrier gas flowing at 100 mL min^{-1}. The desorbed VOCs were captured in a cold trap at −25°C for 5 minutes before undergoing a second thermal desorption step at 320 °C for 5 min at a reverse helium flow rate of 100 mL min^{-1}. A CP-wax column (60 m length, 0.25 mm diameter, 0.25 μm film thickness) was employed for VOC separation in the GC system. For quantitative analysis, the oven temperature was programmed as follows: initial hold at 40 °C for 5 min, ramping at 6 °C min^{-1} to 220 °C, followed by a 20-minute hold at 220 °C (total run time: 60 min). The interface and ion source temperatures in the MS system were maintained at 230 °C. VOCs were monitored in both total ion chromatogram (TIC) and extract ion chromatogram (EIC) modes. The EIC mode was utilized for quantification of each VOC based on major ions identified in their spectra, while other VOCs were examined using TIC mode across a mass range of 35–500 *m/z*. The instrument settings for TD-GC-MS are detailed in Table S3 (a).

2.3.2. HPLC-UV system

All liquid samples (DNPH cartridge solvent extraction and final WS) of CCs were analyzed by Han PLC-UV system (LC-2010, Shimadzu, Japan) equipped with an autosampler (SIL-20A), pump (LC-20AD), oven (CTO-20A), and UV detector (SPD-20A) (Table S3 (b)). All liquid samples were injected into the inlet of the HPLC system at 20 μL by the autosampler. The target analytes were separated on an Extend-C18 column (length: 250 mm, diameter: 4.6 mm, particle size: 5 μm, Agilent, USA) using a mobile phase of acetonitrile: water (70:30, v/v) at a fixed flow rate of 1.5 mL min^{-1} at 30 °C. The separated analytes were detected by the UV detector at a wavelength of 360 nm.

2.4. Collection of VOCs and CCs in the smoking room

A 33.8 m^3 smoking booth was used for the cigarette experiments. The pollution status of VOCs/CCs due to the consumption of HNB in the smoking booth was investigated based on number of cigarettes (n = 1, 3, and 6) and ventilation status of the smoking booth (closed vs. open). In this study, no mechanical ventilation system was applied in the booth. The "open-door" condition implies passive air exchange by opening the door of booth to exchange outdoor air, whereas the "closed-door" condition is for no such exchange. Hence, when the door remains closed, there is no active or passive ventilation (mechanical or natural). The air exchange rate (AER) in the smoking booth during short- sampling under closed-door conditions can be assumed to approach zero. The quantitative analysis of VOCs/CCs released from HNB cigarettes and 1R6F as reference followed the procedures developed in our previous study [30] (Fig. 1).

To collect mainstream smoke for analysis, HNB cigarettes were smoked under the puffing conditions recommended by the ISO 3308:2000 standard (11 puffs per cigarette, 35 mL per puff, 2 s duration, and 30 s interval) [32]. These HNB smoke samples were generated using an IQOS heating device and drawn into a 50 mL gas-tight syringe (SGE, Australia) via a Teflon tube connected to the cigarette filter. The same syringe and setup were employed for collecting smoke for the 1R6F reference cigarettes to ensure consistency across sample types. The collected smoke was manually released from the syringe at a central location of the smoking booth to simulate HNB-smoking conditions and uniform dispersion of smoke. The samples were analyzed from the adsorption tube (VOCs) at a flow rate of 100 mL min^{-1} (3 min) and from the DNPH cartridge (CCs) at 1,000 mL min^{-1} (5 min), respectively. The adsorption tube and DNPH cartridge were analyzed along with blank samples by a TD-GC-MS and an HPLC-UV system, respectively. Elution of the CCs collected in the DNPH cartridge was carried out in 5 mL of acetonitrile, and the eluates were analyzed using an HPLC-UV system. The basic experimental setup is summarized in Table 1. In each experiment, 1, 3, or 6 HNB cigarettes were smoked, and these quantities were designated by cigarette type, such as H6 for six HNB cigarettes.

The sampling cycle for T_0, T_1, T_2, and T_3 is defined in Table 2. Background air before generation of smoke was also collected for baseline measurements at T_0. The ventilation conditions in the smoking booth were considered a key variable, with a detailed discussion of opening/closing effects provided in later sections. The collection of smoke samples was performed over 40 minutes. After collection of background air at T_0, the smoke samples were collected at the three times, each for 5 minutes. Table 2 shows details of the sample collection such as experimental phase, sampling time, total duration, and time-specific sampling window for each cycle. All experiments under both open and closed conditions were conducted identically, except that the door in the former case was opened only for a 5-minute sampling period at time points of T_1, T_2, and T_3. VOCs and CCs measurements were

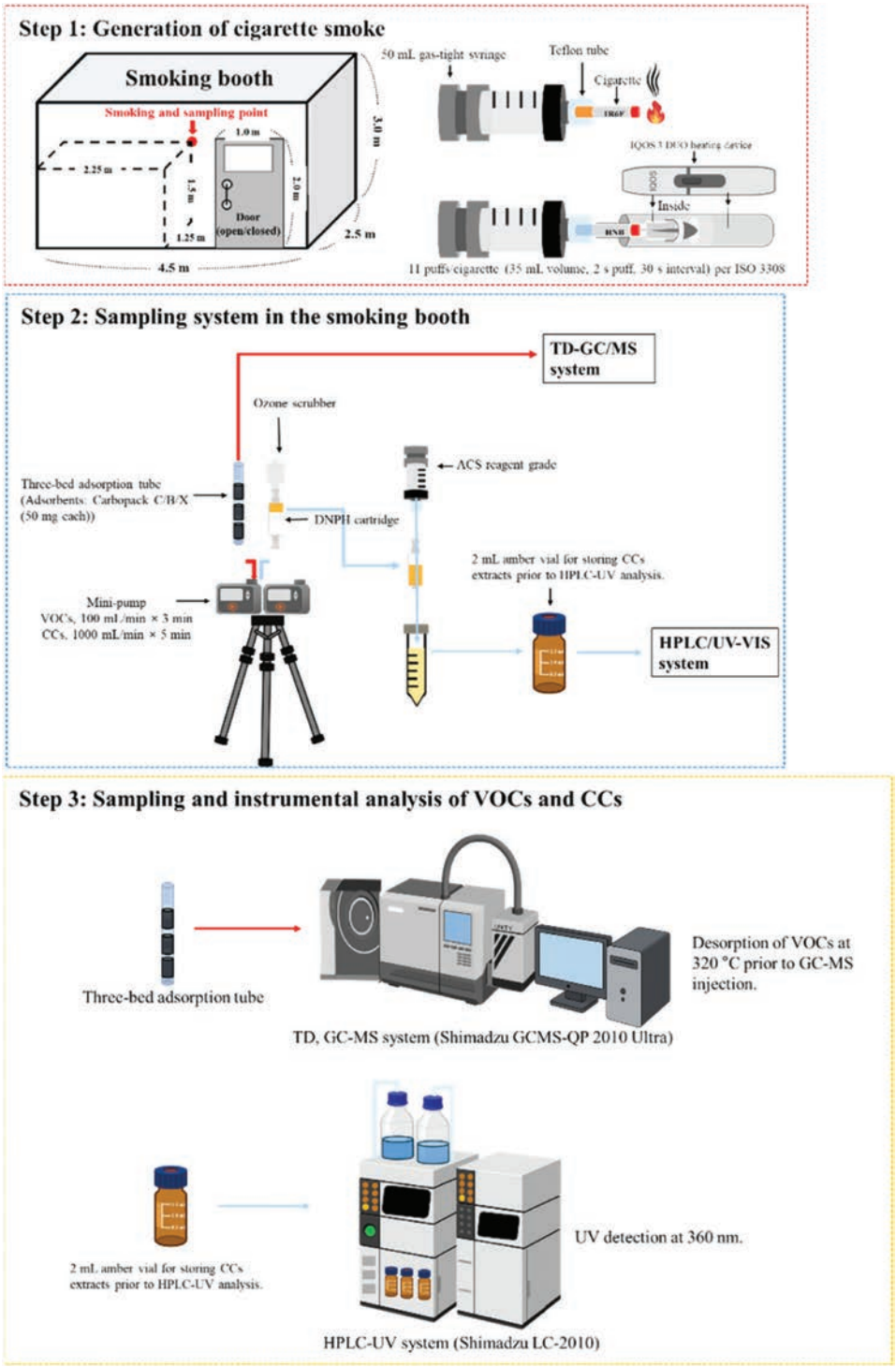

Fig. 1. Experimental setups for collection and analysis of VOCs and carbonyl compounds from cigarette smoke.

conducted under carefully controlled conditions, and representative values are presented with observed variability. Background VOCs fluctuations and reproducibility were monitored and are discussed in Sections 3.1–3.2. Each of all three smoking conditions (1, 3, and 6 cigarettes) was tested in separate trials with full ventilation of the booth between experiments to prevent residual effects. Prior to each trial, the smoking booth was ventilated overnight with the door fully open and a fan in operation to ensure adequate flushing of residual pollutants. As a result, T_0 represents a clean background state before smoke generation and is not directly affected by prior tests.

Table 1
The experimental variables to analyze cigarette smoke in a designated smoking room.

Order	Variables	Parameter
1	Cigarette type	HNB (H) and 1R6F (R) as reference
2	Number of cigarettes	1, 3, and 6 sticks
3	Sampling time	0, 5,10, and 20 min
4	Closed/open	Closed (C) and Open (O) door
5	Generation method of cigarette smoke	35 mL min^{-1} puff volume, 2 s puff duration, 30 s puff interval, and a total of 11 puffs
6	Analysis method	VOCs TD-GC-MS CCs DNPH cartridge-HPLC-UV system

*The numbers after cigarette type of R (R1, R3, and R6) and H (H1, H3, and H6) denote the number of cigarettes smoked.

Table 2
Structured timeline of cigarette smoke generation and sampling events in the smoking booth.

Order	Cycle	Experiment Phase	Time (min)		
			Break Interval	Sampling Time	Total Duration
1	T_0	Sampling	0	5 (0–5)*	5
2	-	Smoke generation	0	5 (5–10)	5
3	T_1	Sampling	5	5 (15–20)	10
4	T_2	Sampling	5	5 (25–30)	10
5	T_3	Sampling	5	5 (35–40)	10

* Note: Time information inside parentheses indicates the *'Time-Specific Sampling Window'* within the total sampling duration.

2.5. Calculation of the concentration levels of VOCs and CCs

Quantitation of the compounds collected from the smoking booth was performed using the following equation:

$$\frac{VOC}{CC}concentration(ppb) = \frac{Peak\ area}{RF} \times \frac{MW}{MV} \times \frac{V_s}{1,000}, \quad (1)$$

where the response factor (RF, ng^{-1}) represents the calibration-derived sensitivity for each target compound. Molecular weight (MW, g mol^{-1}) and molar volume (MV, 24.3 L mol^{-1} at 25 °C and 1 atm) were calculated under standard gas-phase conditions. The sampled volume (V_s, mL or L) refers to the total air volume collected during each sampling event. For VOC analysis, a volume of 300 mL was collected using a vacuum pump at a flow rate of 100 mL min^{-1} over 3 minutes. For CCs, a volume of 5 L was sampled at 1 L min^{-1} for 5 min using a DNPH cartridge. The 14 standardized VOCs were designated as G_1, the 17 reference-calibrated VOCs as G_2, and the 10 directly calibrated CCs as G_3. Unlike G_1 and G_3, the G_2 were quantified using reference-based calibration because certified primary standards were not available for all G_2 compounds based on CLASS approach as explained above (e.g., [28,48]). In this study, the TVOC concentration was determined by summing the values of all compound concentrations and its respective carbon number for each of the three groups (i.e., G_1, G_2, and G_3) [48]. The TVOC was computed using the following equation:

$$TVOC\ concentration(ppbC) = \sum VOC_i \times C_i \quad , \quad (2)$$

where VOC_i and C_i represent the concentration and carbon number of each compound, respectively. Compounds from the G_1, G_2, and G_3 groups were included in the calculation

2.6. Health risk assessment

The health risk assessment is a widely recognized methodology developed by the US Environmental Protection Agency (EPA) to evaluate potential health risks associated with exposure to both carcinogenic and non-carcinogenic substances [15]. The health risk assessment framework consists of four essential steps: (1) Hazard identification of substances of concern; (2) Exposure assessment to quantify the extent and pathways of exposure; (3) Toxicity or dose-response evaluation to determine the relationships between exposure level and potential health effects; and (4) Risk characterization, which integrates the previous findings to estimate overall health risks and their significance [9].

In this study, the health risks associated with indoor air pollutants emitted from cigarette smoking and cooking activities were evaluated using the Hazard Quotient (HQ) and Incremental Lifetime Cancer Risk (ILCR) [50]. Specifically, the HQ and ILCR were used as quantitative metrics to assess the potential non-carcinogenic and carcinogenic risks of indoor smoke (e.g., cigarette smoke and cooking activities), respectively [50]. Indirect exposure concentration (EC_i) and direct exposure concentration (EC_d) were calculated to assess exposure scenarios (Eqs. 3 and 4). EC_i represents indirect exposure (e.g., third-hand smoke) to pollutants in the smoking environment. Likewise, the EC_d denotes direct exposure (e.g., second-hand smoke) to the pollutants during smoking activity (e.g., the person directly involved in cigarette smoking or cooking activities).

$$EC_i = \frac{C_i \quad \times ET \times EF \times ED}{BW \times DIR \times AT} \quad (3)$$

$$EC_d = \frac{C_d \quad \times IR \times ET \times EF \times ED}{BW \times DIR \times AT}, \quad (4)$$

where BW (kg) represents the average body weight of an individual, and DIR (m^3/day) denotes the daily inhalation rate (i.e., volume of air inhaled per day), which varies by individual [5]. As such, it influences personal exposure to airborne pollutants [4]. C_i represents the concentration (μg/m^3) of each compound under background conditions at T_0. C_d implies the concentration (μg/m^3) during active cigarette smoking at T_1. Daily exposure time (ET) refers to the average duration of exposure per day, which is assumed to be 8 hr [46]. Annual exposure frequency (EF) represents the average number of days per year, which is set to 250 days. Exposure duration (ED) is the total duration of exposure over an expected individual lifetime, which is assumed to be 25 years (standard occupational exposure period) [41,43]. For direct exposure, the inhalation rate (IR) was set to 1.00 m^3/hour, reflecting the average respiratory rate of adults during light activity [6,16]. The average time (AT) for carcinogenic compound lifetime was set as 70 years [11]. Subsequently, the EC_i and EC_d values were used to calculate both HQ and ILCR under realistic exposure scenarios. The HQ for cumulative non-carcinogenic risks was calculated using Eq. (5):

$$HQ = \frac{EC_i\ or\ EC_d}{RfC_i\ or\ RfC_d}. \quad (5)$$

The ILCR for incremental lifetime cancer risk was calculated using Eq. (6):

$$ILCR = EC_i\ or\ EC_d \times IUR. \quad (6)$$

where RfC and IUR (μg/m^3) denote the chronic inhalation reference concentration of each compound (mg/m^3) and the estimated inhalation unit risk for each compound, respectively. The ILCR values were categorized as serious risk ($> 1.0 \times 10^{-5}$), potential risk (between 1.0×10^{-5} and 1.0×10^{-6}, and negligible risk ($< 1.0 \times 10^{-6}$). Similarly, HQ > 1 indicates the potential for non-carcinogenic risk, with values less than 1 suggesting minimal risk.

3. Results and discussion

3.1. Background levels of VOCs in the smoking booth

In this research, six experiments were designed to assess the concentration levels of VOCs released from HNB smoking using two key variables: number of cigarettes (1, 3, and 6: n = 3) and smoking booth status (open (O) vs. closed (C): n = 2). The concentrations of each VOC in three VOC groups (e.g., G_1, G_2, and G_3) measured at T_0 (prior to cigarette smoke generation) represent the background levels in the smoking booth and are summarized in Table 3. The concentration levels of G_1, G_2, and G_3 were significantly higher in the closed system than in the open system, with respective mean values of 253 ppbC and 163 ppbC (Table 3). This difference between closed and open conditions is further supported by the average concentrations derived for each group: G_1 (121/85.0 ppbC), G_2 (88.3/52.1 ppbC), and G_3 (43.9/26.4 ppbC). Similarly, G_1 VOCs in the closed/open system were dominated by 1,3-butadiene, benzene, and toluene with mean values of 6.06/29.0, 1.14/

Table 3
Background (T_0) concentrations of VOCs and CCs measured in a smoking booth open-door and closed-door.

Order	Compound	Unit	Parameter							
			C-1[a]	C-3	C-6	Mean of concentration (T_0) from C-1,3,6	O-1	O-3	O-6	Mean of concentration (T_0) from O-1,3,6
			T_0[b]	T_0	T_0		T_0	T_0	T_0	
(a) G_1 (VOCs quantified through direct calibration using primary standards)										
1	1,3 butadiene*	ppb	6.23	2.89	9.06	6.06	**0.40**	86.1	0.62	29.0
2	Acrylonitrile		**0.72**[d]	3.78	**0.72**	1.74	**0.72**	**0.72**	**0.72**	0.72
3	Isoprene		**0.79**	17.3	2.53	6.87	**0.79**	**0.79**	**0.79**	1.88
4	Methyl ethyl ketone		**1.01**	**1.01**	**1.01**	1.01	**1.01**	**1.01**	**1.01**	1.01
5	Benzene		**0.37**	**0.37**	2.68	1.14	**0.37**	8.58	3.42	4.12
6	Toluene		6.30	8.06	9.09	7.82	**1.17**	4.80	7.07	4.35
7	p-Xylene		**0.44**	**0.44**	**0.44**	0.44	**0.44**	**0.44**	**0.44**	0.44
8	m-Xylene		**0.70**	**0.70**	**0.70**	0.70	**0.70**	**0.70**	**0.70**	0.70
9	o-Xylene		**0.36**	**0.36**	**0.36**	0.36	**0.36**	**0.36**	**0.36**	0.36
10	Styrene		0.24	1.11	0.53	0.63	**0.23**	**0.23**	**0.23**	0.23
11	o-Cresol		**0.33**	**0.33**	**0.33**	0.33	**0.33**	**0.33**	**0.33**	0.33
12	Phenol		**0.06**	0.35	2.36	0.92	**0.06**	0.49	**0.06**	0.20
13	p-Cresol		**0.11**	**0.11**	**0.11**	0.11	0.76	**0.11**	**0.11**	0.33
14	m-Cresol		**0.13**	**0.13**	**0.13**	0.13	**0.13**	**0.13**	**0.13**	0.13
15	G_1	ppbC[c]	70.9	105	187	121	5.32	126	123	85.0
(b) G_2 (VOCs quantified based on CLASS approach)										
16	2,4-Dimethylundecane	ppb	3.42	0.33	4.81	2.85	0.37	0.77	1.78	0.97
17	2,4-Dimethylheptane		1.94	2.52	0.13	1.53	0.35	0.04	0.86	0.42
18	Ethyl Acetate		5.73	8.23	3.43	5.80	-*	2.36	0.46	1.41
19	Nonane		1.86	0.24	0.22	0.77	0.19	0.53	0.24	0.32
20	Dodecane		-	-	-	-	0.61	-	-	0.61
21	2-Ethyl-decane		-	-	-	-	-	-	-	-
22	2-Methyl−3-ethylheptane		-	-	-	-	-	-	-	-
23	2,5,5-Trimethylheptane		-	-	-	-	-	-	-	-
24	4,6-Dimethyldodecane		-	-	-	-	-	-	-	-
25	Hendecane		-	-	-	-	-	-	-	-
26	n-Cetane		-	-	-	-	-	-	-	-
27	Tetradecane		-	-	-	-	-	-	-	-
28	Trioxane		-	-	-	-	1.34	-	-	1.34
29	Naphthalene		-	-	-	-	0.40	-	-	0.40
30	Benzaldehyde		-	-	-	-	1.67	-	-	1.67
31	1-Methylnaphthalene		-	-	-	-	0.28	-	-	0.28
32	Benzenemethanol		-	-	3.14	3.14	1.10	4.69	2.39	2.73
33	G_2	ppbC	102	62.1	101	88.3	47.3	57.4	51.6	52.1
(c) G_3 (Carbonyl compounds quantified via DNPH-HPLC with certified standards)										
34	Formaldehyde	ppb	1.76	1.91	3.39	2.35	**1.38**	**1.38**	**1.38**	1.38
35	Acetaldehyde		2.96	3.03	2.57	2.85	2.12	2.98	3.30	2.80
36	Acrolein		**0.61**	**0.61**	**0.61**	0.61	**0.61**	**0.61**	**0.61**	0.61
37	Acetone		3.63	9.20	9.73	7.52	3.83	6.53	2.19	4.18
38	Propionaldehyde		0.56	0.77	**0.55**	0.63	**0.55**	**0.55**	0.59	0.56
39	Crotonaldehyde		**0.97**	**0.97**	**0.97**	0.97	**0.97**	**0.97**	**0.97**	0.97
40	Butyraldehyde		0.95	**0.90**	1.10	0.98	**0.90**	**0.90**	**0.90**	0.90
41	Benzaldehyde		1.51	**1.18**	1.76	1.48	**1.18**	1.84	1.43	1.48
42	Isovaleraldehyd		1.32	**0.99**	**0.99**	1.10	**0.99**	**0.99**	**0.99**	0.99
43	Valeraldehyde		1.12	**0.81**	**0.81**	0.91	**0.81**	**0.81**	**0.81**	0.81
44	G_3	ppbC	48.4	37.9	45.4	43.9	15.7	38.5	25.0	26.4
(d) Total VOCs										
45	TVOC	ppbc	221	205	334	253	68.4	222.1	200	163

Note: For measurements below the method detection limit (MDL), values were replaced with the MDL values and are underlined for clarity. Acronyms for common VOCs are defined in parenthesis and used here and in other Tables. The detailed information of each compound is also given in Table S1.

[a] Case codes indicate the chamber's ventilation state (either closed (C) or open (O)) along with the number of cigarettes tested (1, 3, or 6).

[b] Sampling for both HNB cigarettes was conducted over a 5-minute period, with analysis performed at T_0 (prior to smoke generation, as a blank measurement).

[c] The total VOC (TVOC) concentration was calculated as the sum of VOCs, CCs, and unidentified VOCs concentrations, using a corrected response factor (RFc) from calibration data in ppbC units. Values below the MDL were excluded from the TCC calculation.

[d] All average concentrations were calculated using the available and MDL-substituted values (underlined) to ensure complete numerical representation across all compounds.

* The symbol '–' indicates compounds in the G2 VOC group that were quantified using reference-based calibration in the absence of compound-specific standards and represents cases with values below method detection limits (MDLs).

4.12, and 7.82/4.35 ppb, respectively (Table 3). Likewise, among G_2 VOCs in a closed/open system, 2,4-dimethylundecane, 2,4-dimethylheptane, and ethyl acetate were at 2.85/0.97, 1.53/0.42, and 5.80/1.41 ppb, respectively (Fig. 2). For the G_3 VOCs, formaldehyde, acetaldehyde, and acetone were most prominent, with average concentrations of 2.35/1.38, 2.85/2.80, and 7.52/4.18 ppb, respectively. This confirms that the background concentration levels of G_1, G_2, and G_3 VOCs in the open condition were approximately 1.4–1.7 times lower than those in the closed system, corresponding to reductions of 29.8 %, 41.0 %, and 39.9 %, respectively (Table 3). It is reasonable to attribute the residual presence of $G_1/G_2/G_3$ VOCs in the background air to the desorption of previously adsorbed pollutants from surfaces within the smoking booths [8]. The elevated levels of these VOCs suggest that harmful air pollutants in enclosed environments can continue to be released from objects even in the absence of active cigarette smoking [3]. Additional background data of 1R6F cigarette emissions at T_0 under similar conditions are summarized in Table S4, providing a comparative baseline for reference cigarette impact under closed and open settings.

3.2. Analysis of VOCs in the closed/open chamber system

This study investigated the impacts of ventilation conditions (closed vs. open) on the concentrations of G_1, G_2, and G_3 VOC groups emitted from six HNB (H6) cigarettes (Table 4). For clarity, all VOC data refer to closed conditions unless stated otherwise. The highest TVOC concentration—1347 ppbC—was recorded under the H6 condition (six cigarettes in a closed booth), highlighting the combined effects of limited ventilation and high cigarette load. The concentration profiles of G_1, G_2, and G_3 VOCs followed a similar trend to that of TVOCs (Table 4). Among the targeted G_1 VOCs, isoprene was the most abundant compound in HNB smoke. Under H6 at T_1, isoprene reached a concentration of 14.2 ppb, followed by toluene (10.5 ppb) and 1,3-butadiene (7.83 ppb), representing the top three contributors (Table 4). Among G_2 VOCs, dodecane was the dominant compound, reaching 16.8 ppb under the H6 condition, followed by ethyl acetate (15.2 ppb) and undecane (14.4 ppb). For G_3 VOCs, the highest concentrations were observed for acetaldehyde (17.6 ppb), acetone (15.4 ppb), and formaldehyde (7.45 ppb) (Fig. 3). The impact of ventilation was evident under open conditions, with concentrations of G_1, G_2, and G_3 compounds reduced from 228 to 147 ppbC (35.5 %), 960–245 ppbC (74.5 %), and 159–24.6 ppbC (84.5 %), respectively, compared to closed-booth conditions (Table 4).

These differences highlight the distinct emission profiles of VOCs under open versus closed ventilation conditions. It is acknowledged that persistent release of VOCs that were adsorbed onto the chamber's interior surfaces may have contributed to elevated T_0 concentrations, particularly under closed-door conditions. This surface effect could, in some cases, result in background levels approaching or exceeding post-smoking levels when only a small number of sticks are used. The findings show that ventilation significantly affects indoor concentrations of VOCs and CCs—closed conditions lead to the buildup of harmful compounds, whereas open conditions help mitigate their accumulation. This underscores the crucial role of ventilation in indoor air quality, particularly in smoking environments. Notably, HNB cigarettes exhibited a considerably lower impact on indoor air pollution than control cigarettes, with reduced concentrations of G_1, G_2, and G_3 compounds, suggesting a comparatively lower potential health risk.

3.3. Analysis of VOCs in a closed chamber system with an increasing number of cigarettes

The effect of increasing number of HNB cigarettes on the VOC level in the chamber was investigated in reference to 1R6F cigarettes (Table 4 and S5). The TVOC level increased proportionally with the number of cigarettes smoked, showing a general pattern for consistent and monotonic rise (Fig. 4),. Specifically, the TVOC occurred in the order of H6 (1347 ppbC) > H3 (711 ppbC) > H1 (335 ppbC) (Table 4). The concentration levels of individual VOC groups (e.g., G_1, G_2, and G_3) exhibited similar trends to that of the TVOC. As the number of HNB cigarette sticks increased from one to six, the concentrations of G_1, G_2, and G_3 compounds increased accordingly, ranging from 97.3 to 228 ppbC, 183–960 ppbC, and 55.9–159 ppbC, respectively (Table 4 and Fig. 4).

Among the top three G_1 VOCs emitted from HNB cigarettes, the highest concentrations of H1, H3, and H6 were measured for isoprene (0.79, 5.64, 14.2 ppb, respectively), followed by toluene (7.99, 10.4, and 10.5 ppb) and 1,3-butadiene (10.4, 4.83, and 7.83 ppb). For G_2 VOCs, many compounds were not detected at H1 conditions, and dodecane was the most prominent, with the concentration increasing from undetectable at H3 to 16.8 ppb at H6. Ethyl acetate levels at H1, H3, and H6 were 3.10, 10.1, and 15.2 ppb, respectively, while those of hendecane were not detected, 11.5, and 14.4 ppb. If the H1, H3, and H6 values are compared for G_3 group compounds, acetaldehyde was dominant (1.11, 14.9, and 17.6 ppb, respectively), followed by acetone (8.73, 12.4, and 15.4 ppb) and formaldehyde (9.33, 1.48, and 7.45 ppb) (Table 4).

The HNB data obtained in this study were compared to those of the 1R6F cigarette. The concentrations of G_1, G_2, and G_3 compounds

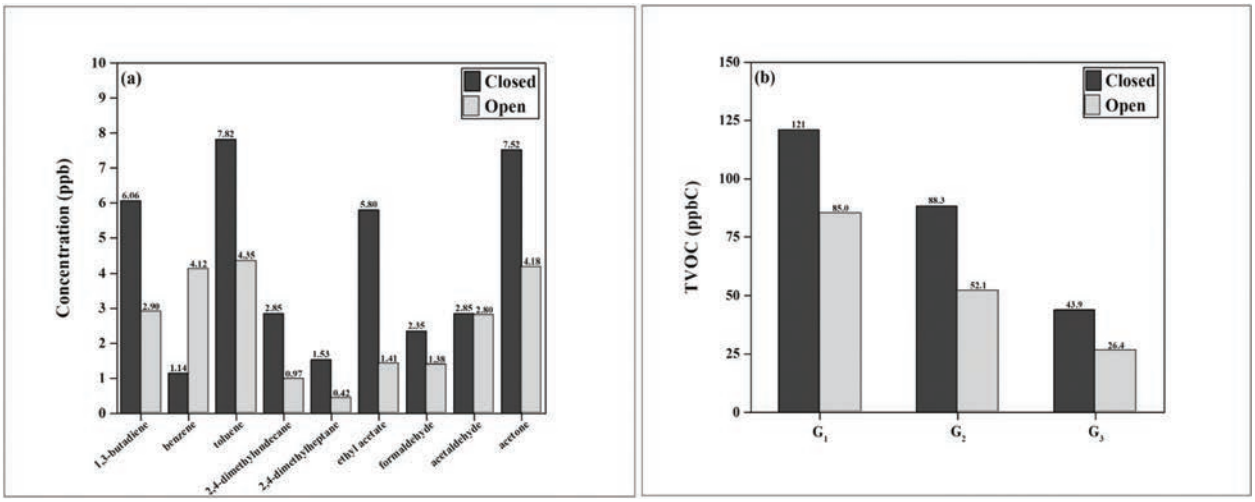

Fig. 2. Background concentrations of major VOCs (G_1, G_2, and G_3) and their total ppbC levels measured under closed and open ventilation conditions prior to cigarette smoke generation. (a) Compound-specific concentrations of G_1, G_2, and G_3 VOCs. (b) Individual VOC groups (in ppbC) for G_1, G_2, and G_3.

Table 4
Summary of volatile organic compound (VOC) concentration levels in HNB emission samples, considering sampling cycle and ventilation conditions.

Order	Compound	Unit	Parameter																	
			C-1			C-3			C-6			O-1			O-3			O-6		
			T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3
(a) G_1 (VOCs quantified through direct calibration using primary standards)																				
1	1,3 butadiene	ppb	10.4	8.95	8.05	4.83	**0.91**	**0.91**	7.83	7.60	6.18	**0.91**	**0.91**	**0.91**	6.35	4.55	3.90	6.33	5.85	5.10
2	Acrylonitrile		**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**
3	Isoprene		**0.79**	**0.79**	**0.79**	5.64	2.98	**0.79**	14.2	11.5	4.68	**0.79**	**0.79**	**0.79**	5.04	4.48	4.74	5.64	4.38	4.04
4	Methyl ethyl ketone		**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**	**1.01**
5	Benzene		**0.37**	**0.37**	**0.37**	**0.37**	**0.37**	**0.37**	1.40	1.23	2.20	2.43	**0.37**	**0.37**	1.23	**0.37**	**0.37**	6.30	2.02	2.02
6	Toluene		7.99	6.94	6.73	10.4	7.66	7.06	10.5	7.37	7.77	**1.17**	**1.17**	**1.17**	4.59	**1.17**	**1.17**	7.37	6.81	6.6
7	p-Xylene		**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**	**0.44**
8	m-Xylene		**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**	**0.70**
9	o-Xylene		**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**
10	Styrene		**0.23**	0.28	0.28	1.11	0.79	0.63	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**
11	o-Cresol		**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**
12	Phenol		**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	1.14	0.94	0.72	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	0.27	0.44	0.25
13	p-Cresol		**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	2.01	1.29	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**
14	m-Cresol		**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	1.96	1.31	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**
15	G_1	ppbC	97.3	86.6	81.5	129	74.8	54.4	228	178	126	14.6	0.00	0.00	90.1	40.6	39.3	147	111	102
(b) G_2 (VOCs quantified based on CLASS approach)																				
16	2,4-Dimethylundecane	ppb	1.52	0.29	-*	3.55	3.24	2.19	3.47	2.91	2.44	-	-	-	-	-	-	1.95	-	-
17	2,4-Dimethylheptane		-	-	-	1.06	1.02	0.58	2.17	1.83	1.00	-	-	-	-	-	-	-	-	-
18	Ethyl Acetate		3.10	-	-	10.1	8.80	13.8	15.2	12.9	11.9	-	-	-	-	-	-	2.78	-	-
19	Nonane		-	-	-	1.13	0.36	0.26	3.01	2.37	0.21	-	-	-	-	-	-	1.64	1.34	1.23
20	Dodecane		-	-	-	-	-	-	16.8	11.6	5.33	-	-	-	-	-	-	0.75	0.74	0.70
21	2-Ethyl-decane		12.5	-	-	4.76	1.55	1.33	5.46	4.60	3.68	-	-	-	-	-	-	2.61	2.52	2.26
22	2-Methyl−3-ethylheptane		-	-	-	-	-	-	4.25	0	0	-	-	-	-	-	-	-	-	-
23	2,5,5-Trimethylheptane		-	-	-	-	-	-	5.22	4.98	4.47	-	-	-	-	-	-	-	-	-
24	4,6-Dimethyldodecane		-	-	-	6.46	7.64	-	7.57	3.78	0	-	-	-	-	-	-	3.40	2.79	-
25	Hendecane		-	-	-	11.5	14.4	-	14.4	-	-	-	-	-	-	-	-	1.09	0.56	0.38
26	n-Cetane		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
27	Tetradecane		-	-	-	1.60	-	-	1.93	-	-	-	-	-	-	-	-	-	-	-
28	Trioxane		-	-	-	5.23	5.07	4.73	9.20	5.40	3.57	-	-	-	-	-	-	-	-	-
29	Naphthalene		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.78	1.64	-
30	Benzaldehyde		-	-	-	5.67	4.93	-	-	-	-	-	-	-	-	-	-	2.84	-	-
31	1-Methylnaphthalene		-	-	-	1.10	1.02	-	10.2	-	-	-	-	-	-	-	-	2.36	6.85	-
32	Benzenemethanol		-	-	-	2.51	2.43	2.10	2.16	1.37	-	-	-	-	5.27	1.96	1.69	1.47	1.18	0.99
33	G_2	ppbC	182	3.83	0.00	487	451	136	960	450	254	0.00	0.00	0.00	36.9	13.7	11.8	245	197	57.7
(c) G_3 (Carbonyl compounds quantified via DNPH-HPLC with certified standards)																				
34	Formaldehyde	ppb	9.33	7.90	**1.38**	1.48	1.47	1.43	7.45	9.89	6.97	**1.38**	**1.38**	**1.38**	**1.38**	**1.38**	**1.38**	3.43	2.65	**1.38**
35	Acetaldehyde		**1.11**	**1.11**	**1.11**	14.9	11.7	9.80	17.6	13.8	11.9	1.79	1.60	1.34	3.23	2.22	2.08	4.58	3.75	1.88
36	Acrolein		**0.61**	**0.61**	**0.61**	**0.61**	**0.61**	**0.61**	12.0	10.2	8.13	**0.61**	**0.61**	**0.61**	**0.61**	**0.61**	**0.61**	**0.61**	**0.61**	**0.61**
37	Acetone		8.73	**0.67**	**0.67**	12.4	12.3	8.00	15.4	14.3	12.9	1.24	**0.67**	**0.67**	**0.67**	**0.67**	**0.67**	3.08	2.63	1.51
38	Propionaldehyde		0.60	**0.55**	**0.55**	1.52	**0.55**	**0.55**	**0.55**	0.64	**0.55**	7.46	5.54	4.60	0.62	0.69	**0.55**	0.91	0.58	0.87
39	Crotonaldehyde		**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**
40	Butyraldehyde		**0.90**	**0.90**	**0.90**	1.10	0.99	0.97	1.26	1.18	1.14	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**	**0.90**
41	Benzaldehyde		2.66	3.20	4.04	1.91	1.63	1.39	1.94	1.53	1.96	**1.18**	**1.18**	**1.18**	**1.18**	**1.18**	**1.18**	**1.18**	**1.18**	**1.18**
42	Isovaleraldehyd		**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	1.73	1.54	1.16	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**
43	Valeraldehyde		**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	1.02	1.01	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**	**0.81**
44	G_3	ppbC	55.9	30.3	28.3	94.0	80.1	61.6	159	143	120	29.7	19.8	16.5	8.31	6.49	4.16	24.6	19.8	10.9
(d) Total VOCs																				
45	TVOC	ppbc	335	121	110	711	606	252	1347	771	500	44.3	19.8	16.5	135	60.8	55.3	416	328	171

[a]Case codes indicate the chamber's ventilation state (closed (C) or open (O)) along with the number of cigarettes tested (1, 3, or 6).
[b]The sampling process for both HNB cigarettes spanned a total of 5 minutes, with T_1 representing 5–10 minutes, T_2 for 15–20 minutes, and T_3 for 25–30 minutes following smoke sample release.
[c]TVOC was calculated as the sum of VOCs, CCs, and unidentified VOCs based on a corrected response factor (RFc) from calibration data in ppbC. Values below the MDL were excluded from the TVOC calculation.
*The symbol '–' indicates compounds belonging to the G_2 VOC group that were quantified using reference-based calibration in the absence of compound-specific standards and represents a case below method detection limits (MDLs).
Note: For measurements below the method detection limit (MDL), values were replaced with the MDL values and underlined for clarity. And abbreviations are defined in Table S1.

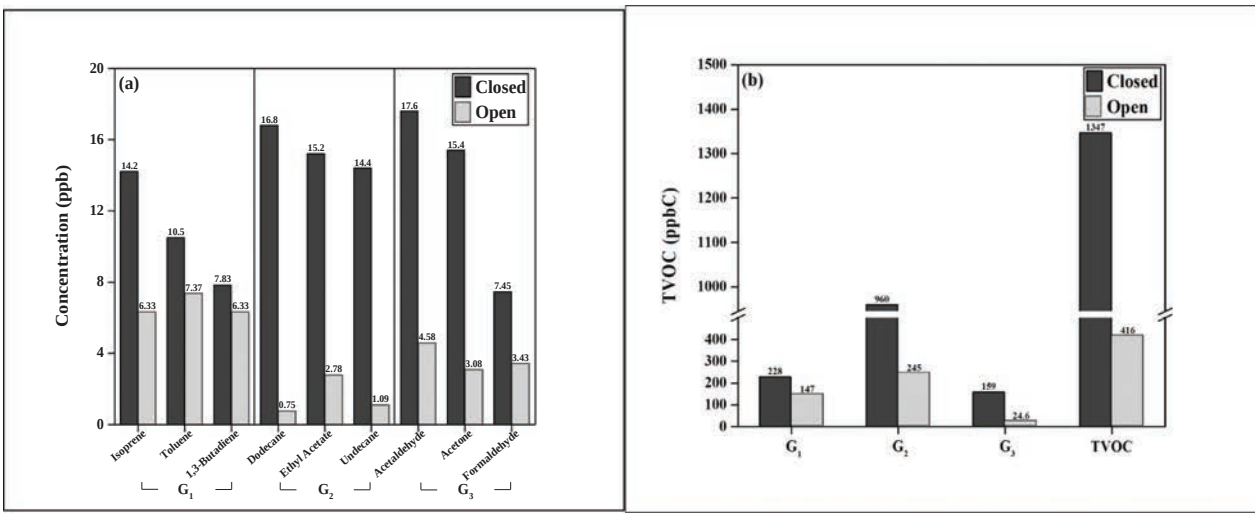

Fig. 3. Effect of ventilation on VOC emissions from six HNB cigarettes. (a) Concentrations of key G_1, G_2, and G_3 VOCs under closed and open conditions. (b) Corresponding VOC groups plus total TVOC.

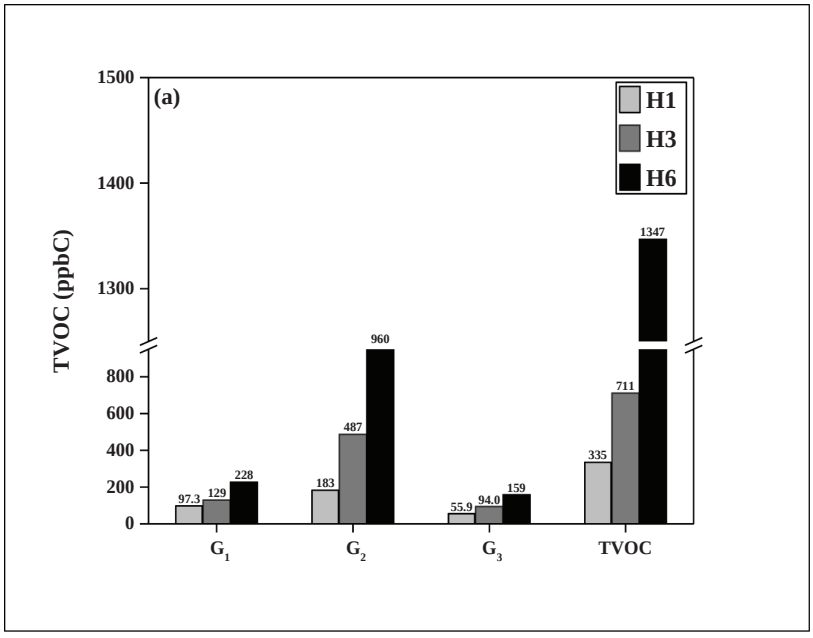

Fig. 4. VOC concentration levels measured in relation to number of HNB cigarettes smoked in a closed chamber. Bar plots show group-level concentrations (G_1, G_2, and G_3) and TVOC values for H1, H3, and H6 conditions, illustrating additive emission behavior with increasing cigarette number.

increased from R1 to R6 from 228 to 10,498 ppbC (4500 %), 960–2835 ppbC (195 %), and 159–1501 ppbC (844 %) under closed conditions, respectively (Table 4). The experimental data clearly indicated that 1R6F cigarettes emit significantly higher levels of VOCs and CCs compared to HNB products, reflecting large differences in combustion temperature, tobacco composition, and combustion efficiency [52]. Typical HBN cigarettes are consumed at lower temperatures (~300 °C) than 1R6F (600 °C), resulting in 10-fold lower emission of a wide range of air pollutants (TVOC of 1347 ppbC in H6 vs. 14,834 ppbC in R6). Additionally, the presence of more numerous additives in 1R6F cigarettes may contribute to elevated levels of unknown VOCs and CCs. The results of our study underscore the greater impact of traditional cigarettes (1R6F) on indoor air quality and their associated health risks compared to HNB products (Table S5). Nevertheless, despite lower emissions, an increased number of HNB cigarettes leads to a noticeable deterioration in indoor air quality. These findings highlight the importance of limiting cigarette consumption and ensuring adequate ventilation in indoor environments.

3.4. Carcinogenic and non-carcinogenic health impact assessment: Comparative analysis of VOC and CC levels between cigarette smoke and cooking emissions

In this research, the relative significance of HNB smoking was assessed. As various sources contribute to indoor air pollution, it is important to understand the relative contributions of source activities

Table 5
VOC and CC concentrations from HNB and 1R6F cigarettes under various experimental conditions.

Order	Cigarette type	Information of chamber	Closed/ open condition	Number of cigarettes	Concentration(ppb)				Concentration(μg/m^3)				Reference
					FA	AA	B	T	FA	AA	B	T	
1	HNB 1R6F	Smoking booth (interior surfaces are acrylic and glass)33.8 m^3 (width: 4.5 m × length: 2.5 m × height: 3.0 m)	Closed	1	2.78 69.7	54.8 780	0.01 24.2	0.01 32.9	3.42 85.6	98.8 1406	0.01 77.3	0.03 124	[19]
2	HNB 1R6F	Chamber (interior surface is PTFE-coated aluminum)0.2 m^3 (width: 0.56 m × length: 0.56 m × height: 0.64 m)	Closed	1	2.05 60.9	100 69.9	0.85 4.66	1.35 4.67	2.52 74.9	181 126	2.7 14.9	5.1 17.6	[7]
3	HNB 1R6F	Indoor room (glass-fiber filtered air, airtight condition)55.8 m^3 (5.8 × 3.7 × 2.6 m)	Closed	1	1.2 30.5	6.2 47.5	0.3 3.9	0.5 5.1	1.5 36.2	11.2 86.1	0.8 12.4	1.2 19.3	[33]
4	HNB 1R6F	Indoor air quality if the room (controlled environment with temperature and humidity regulation)72.3 m^3	Closed	12	8.30 54.7	3.26 589	0.20 35.4	0.27 28.9	10.2 67.2	5.87 1062	0.639 113	1.03 109	[37]
5	HNB 1R6F	Acrylic exposure chamber (controlled airflow environment)	Closed	6	0.95 34.85	12.9 390	0.01 12.1	0.02 16.4	1.17 42.8	23.4 703	0.032 38.7	0.058 62.0	[21]
6	HNB 1R6F	Smoking booth33.8 m^3 (width: 4.5 m × length: 2.5 m × height: 3.0 m))	Closed	6	7.45[a] 363	17.6 333	1.23 60	7.37 139	9.15 200	31.7 600	3.93 192	27.8 524	This study

Note: Abbreviations are defined in Table S1.
[a] C-6 at T_1 was used as representative data.

(Table 5). Among such sources, cooking emissions are widely recognized as major contributors to decreased indoor air quality. Numerous studies have examined emissions from cooking activities under varying conditions, similar to those of investigations with cigarette smoke (Table 6).

3.4.1. Comparison of VOCs and CCs from cigarette smoke

In this section, the emission levels of VOCs and CCs from HNB cigarettes were evaluated in comparison to those reported for commercial cigarettes. Specifically, as presented in Sections 3.2 and 3.3, benzene/toluene and formaldehyde/acetaldehyde were identified as the dominant G_1 and G_2 compounds in HNB emissions, respectively. Therefore, the concentrations of these representative VOCs were compared with corresponding literature data (Table 5). The HNB results across studies indicate that VOC levels are influenced by number of cigarettes smoked and the size and materials of the cigarettes. In our study, the concentrations of FA, acetaldehyde, benzene, and toluene from H6 cigarettes in were markedly lower than those reported for six 1R6F cigarettes in an acrylic exposure chamber—by factors of 21.9, 18.9, 42.9, and 13.2, respectively [21]. Such patterns were also observed in other studies conducted under comparable conditions. Specifically, the concentration levels of the former three compounds (except acetaldehyde) were approximately 24.2-, 7.7-, and 15.5-fold lower, respectively, than those reported for a single 1R6F cigarette in a 55.8 m^3 indoor environment. These findings highlight the markedly reduced emission characteristics of HNB products. In particular, the drastic reduction in formaldehyde underscores the potential of HNBs to produce less indoor air pollution relative to conventional cigarettes [33]. This elevation in FA, acetaldehyde, benzene, and toluene concentrations reported in previous studies is likely due to the smaller chamber volume, which results in less dilution and thus higher pollutant concentrations per unit volume. The concentrations of the major VOCs such as benzene, toluene, FA, and acetaldehyde in our study were lower by factors of 58.6, 6.10, 20000, and 13900, respectively, than those reported in a smoking booth with interior surfaces of acrylic and glass [19]. Further, they were also lower by factors of 29.8, 0.7, 5.48, and 3.46, respectively, than those measured in chambers with PTFE-coated aluminum walls and floors [7] (Table 5).

In this study, experiments were conducted to independently assess the effects of smoking dose, ventilation condition, and elapsed time after emission. However, it should be acknowledged that these factors may interact each other in real-world scenarios. For instance, higher cigarette loadings may diminish the dilution efficiency of ventilation, leading to disproportionate pollutant buildup. Although interaction effects were

Table 6
Reported concentrations of carbonyl compounds from cooking activities in previous studies.

Order	Study period	Cooking type	Energy source	Place	Pollutant	Concentration (ppb)[a]	Concentration (μg/m^3)	Reference
1	Before 2010	Frying, steaming, barbecuing	Electricity	Kitchen	Formaldehyde/ Acetaldehyde	7.10–364[b]/263	8.72–448/473	[53]
2	2010–2020	Frying and barbecuing	Gas or charcoal	Lab setting /outdoor market	Formaldehyde	1769	2173	[25]
3	2010–202	Frying and barbecuing	LPG	Kitchen	Formaldehyde/ Acetaldehyde	0.65–97.1/ 1.0–41.4	0.8–119.2/ 1.80–74.5	[26]
4	2010–2020	Frying	Electricity	Lab setting	Formaldehyde/Hexanal[d]	18.2/47.4	22.3/194	[29]
5	After 2020	Frying	LPG	Kitchen	Formaldehyde/ Acetaldehyde/Acrolein	27.2/12.9 /< 0.01	33.4/23.2/< 0.02	[13]
6	After 2020	Barbecuing	Electricity	Lab setting	Formaldehyde/Acrolein	287/144	352/331	[45]
7	This study	Barbecuing	LPG	Kitchen	Formaldehyde/ Acetaldehyde	20.4/27.5	25.0/49.6	**This study**[c]

[a] Pollutant concentrations are presented in both parts per billion (ppb) and micrograms per cubic meter (μg/m3) to enable direct comparison between studies.
[b] Ranges indicate the minimum and maximum concentrations reported in the literature under the given experimental conditions.
[c] "This study" refers to the barbecuing experiment performed in a controlled kitchen environment using an LPG source.
[d] Italicized pollutants (e.g., Acrolein, Hexanal) are not the focus of this study but are included here for reference based on previous studies.

not analyzed in this study, their potential influence on indoor pollution from HNB products warrants further investigation.

3.4.2. Comparison of VOCs and CCs from cooking emissions

In this research, efforts were also made to compare VOC emissions from other indoor activities such as cooking practices to help contextualize HNB cigarette emissions within broader indoor exposure scenarios. This comparison is not intended to imply compositional similarity, but rather to illustrate the relative magnitude and types of indoor air pollutants produced a common household activity relative to HNB emissions. The cooking related emission data include measurements from previous literature as well as those obtained based on a cooking-emission scenario designed in this study. Details of the cooking conditions, fuel types, and monitored pollutants are summarized in Table 6. Cooking emissions are also a major source of indoor air pollution, especially those from frying and barbecuing, where incomplete combustion and thermal degradation of food components release harmful pollutants [22]. As shown in Table 6, FA concentrations in cooking emissions exhibit a broad range depending on the cooking method, energy source, and ingredients. For instance, frying, steaming, and barbecuing meat (chicken, pork, and beef) using electrical heating in a kitchen resulted in FA levels ranging from 7.10 to 364 ppb and acetaldehyde levels reaching 263 ppb ([53]b). In contrast, significantly higher FA levels of 1769 ppb were reported in a lab setting and outdoor market containing gas stoves and charcoal grills, emphasizing the substantial impact of fuel type and cooking conditions [25]. Furthermore, FA concentrations ranging from 0.65 to 97.1 ppb and acetaldehyde concentrations of 1.0–41.4 ppb were recorded when frying and barbecuing with liquefied petroleum gas (LPG) in an indoor kitchen [26]. In contrast, significantly lower FA emissions of 18.2 ppb and hexanal levels of 47.4 ppb were observed when frying over electricity in a lab setting, indicating that fewer harmful compounds are generally emitted by electrical heating compared to combustion-based methods [29].

In recent studies focusing on modern cooking practices such as frying using LPG in a kitchen setting, the concentrations of FA and acetaldehyde were measured as 27.2 ppb and 12.9 ppb, respectively, along with trace amounts of acrolein (<0.01 ppb) [13]. Likewise, significantly high FA and acrolein levels of 287 ppb and 144 ppb, respectively, were observed during electrical barbecuing in a lab setting, highlighting the critical influence of cooking method and fuel type on emission profiles [45] (Table 6). The variability in VOC and CC emissions from cooking is evident across studies, indicating that cooking temperature, fuel type, and cooking method influence the emission profile. Notably, combustion-based methods (e.g., gas and charcoal grilling) consistently show higher emissions than electrical cooking. Additionally, the cooking oil and overcooking contribute to aldehyde emissions, particularly when using high-temperature grilling methods. Given that cooking is a daily activity with frequent exposure, its cumulative contribution to indoor air pollution may be substantial. These findings highlight the need to consider both cigarette smoke and cooking emissions in comprehensive indoor air quality management strategies to minimize health risks.

The emissions of VOCs and CCs from cooking activities are controlled by the combined effects of multiple factors such as cooking temperature, type of cooking oil, and energy source. As summarized in Table 5, concentrations of representative compounds (e.g., formaldehyde and acetaldehyde) from HNB cigarette smoke are noticeably lower than those from various cooking scenarios. This comparative analysis highlights the importance of addressing both HNB smoking and cooking emissions in comprehensive indoor air quality assessments. For example, the use of LPG in frying and barbecuing has been shown to generate higher levels of FA and acetaldehyde than electric heating, highlighting the role of combustion fuel in emission levels. Additionally, overcooking and repeated use of cooking oil contribute to increased emission of harmful aldehydes, further elevating the potential health risks associated with indoor cooking activities. In addition, the focus of this study was put primarily on VOC and CC emissions from HNB cigarette smoke. However, it is acknowledged that the secondary reactions, such as those involving indoor ozone, can occur post-emission. These reactions may generate additional oxidized products or secondary aerosols (e.g., organic acids, peroxides), as reported previously [49]. Although this study did not include direct measurement of ozone-induced reactions, this topic warrants further investigation in future work.

3.4.3. Implications for Indoor Air Quality and Health Risks

To evaluate the potential health implications of VOC exposure from HNB cigarette emissions, a non-carcinogenic risk assessment was conducted. In this assessment (Tables 7), 1,3-butadiene exhibited hazard quotients (HQs) of 0.62 at T_0 and 0.33 at T_1—both below the threshold value of 1—indicating no significant non-carcinogenic risk. For other evaluated compounds, such as toluene and formaldehyde, HQ values ranged from 0.0005–0.0002 and 0.02–0.03, respectively, further suggesting negligible non-carcinogenic health effects. Among all evaluated compounds, 1,3-butadiene exhibited the highest hazard quotient (HQ) value, which—although remaining below the threshold of 1—warrants further attention due to its higher risk contribution. In the carcinogenic risk assessment, 1,3-butadiene also had the highest carcinogenic risk potential within the HNB group, with incremental lifetime cancer risk (ILCR) of 3.72×10^{-5} at T0 and 1.97×10^{-5} at T1. Other compounds, such as toluene and formaldehyde, showed ILCR values ranging from 1.72×10^{-6} to 4.28×10^{-6}, falling within the generally acceptable risk range of 1.0×10^{-6} to 1.0×10^{-4}. In contrast, propionaldehyde and other minor compounds demonstrated ILCR values less than 1.0×10^{-6}, indicating negligible carcinogenic risks. For 1R6F cigarettes, however, the non-carcinogenic risk assessment revealed substantial concern for 1,3-butadiene, with HQ values of 1.65 at T_0 and 5.30 at T_1—both exceeding the safety threshold.

These findings underscore a considerable non-carcinogenic risk associated with 1,3-butadiene in emissions from 1R6F cigarettes. In contrast, HQ values of toluene and formaldehyde were in the ranges from 0.003 to 0.002 and from 0.15 to 0.22, respectively. As these values are both below the threshold of concern, non-carcinogenic risks should be minimal. In the carcinogenic risk assessment, 1,3-butadiene demonstrated significantly elevated ILCR of 9.91×10^{-5} at T0 and 3.18×10^{-4} at T_1, exceeding or approaching the upper limit of the acceptable risk range (1.0×10^{-4}). Formaldehyde and toluene also showed potential carcinogenic risks, with ILCR ranging from 1.87×10^{-2} to 2.86×10^{-5} and 3.07×10^{-5} to 1.68×10^{-5}, respectively. Conversely, propionaldehyde exhibited ILCR less than 1.0×10^{-6}, indicating negligible carcinogenic risk [40]. These findings underscore the lower concentrations of hazardous compounds emitted from HNB cigarettes of than 1R6F cigarettes, while certain compounds—particularly 1,3-butadiene—warrant continued monitoring due to their potential contributions to both non-carcinogenic and carcinogenic health risks.

4. Conclusions

Our investigation into indoor air quality in a smoking booth following HNB use revealed several critical insights. A pronounced disparity in VOC and CC concentrations was observed between HNB and traditional 1R6F cigarettes, with the latter emitting significantly higher levels of hazardous compounds such as 1,3-butadiene and isoprene. These differences underscore the substantial impact of cigarette type on indoor air pollution, with HNB products contributing to a notably lower VOC burden. Environmental conditions further influenced pollutant levels—closed-room scenarios intensified the accumulation of emissions, particularly for 1R6F cigarettes. In contrast, HNB cigarettes maintained lower and more stable concentrations under similar conditions, suggesting a reduced impact on indoor air quality. However, certain VOCs, such as MEK, reached concerning levels in HNB smoke, indicating that these products are not entirely without health risks.

In this work, efforts were put to assess emission levels of VOCs and

Table 7
Non-cancer (HQ) and cancer (ILCR) risks of VOCs and CCs emitted from HNB cigarette smoking in closed-booth conditions.

Order	Parameter												
	Compounds	Concentration[a]				EC_i (μg/m³)	EC_d (μg/m³)	RfC[b] (μg/m³)	IUR[c] (μg/m³)$^{-1}$	HQ		ILCR	
		(ppb)		(μg/m³)									
		T_0	T_1	T_0	T_1					T_0	T_1	T_0	T_1
(a) VOCs													
1	1,3 butadiene	6.23	10.4	15.2	23.0	1.24	0.66	2.00	3.00E—05	0.62	0.33	3.72E—05	1.97E—05
2	Acrylonitrile	-*	-	-	-	-	-	2.00	6.80E—05	-	-	-	-
3	Isoprene	-	-	-	-	-	-	3.62	2.00E—05	-	-	-	-
4	Methyl ethyl ketone	-	-	-	-	-	-	5000	NE[d]	-	-	-	-
5	Benzene	-	-	-	-	-	-	30.0	7.80E—06	-	-	-	-
6	Toluene	6.30	7.99	29.0	30.1	2.36	0.86	5000	2.00E—06	0.0005	0.0002	4.73E—06	1.72E—06
7	p-Xylene	-	-	-	-	-	-	100	NE	-	-	-	-
8	m-Xylene	-	-	-	-	-	-	100	NE	-	-	-	-
9	o-Xylene	-	-	-	-	-	-	100	NE	-	-	-	-
10	Styrene	0.24	-	0.70	-	0.06	-	1000	5.00E—07	0.0001	-	2.85E—08	-
11	o-Cresol	-	-	-	-	-	-	6.00	NE	-	-	-	-
12	Phenol	-	-	-	-	-	-	200	NE	-	-	-	-
13	p-Cresol	-	-	-	-	-	-	6.00	NE	-	-	-	-
14	m-Cresol	-	-	-	-	-	-	6.00	NE	-	-	-	-
(b) Reference VOCs													
15	2,4-Dimethylundecane	0.20	-	-	1.52	-	0.04	NE	NE	-	-	-	-
16	2,4-Dimethylheptane	-	-	-	-	-	-	NE	NE	-	-	-	-
17	Ethyl Acetate	0.86	-	-	3.11	-	0.09	1000	NE	-	0.0001	-	-
18	Nonane	-	-	-	-	-	-	NE	NE	-	-	-	-
19	Dodecane	-	-	-	-	-	-	NE	NE	-	-	-	-
20	2-Ethyl-decane	1.78	-	-	12.5	-	0.36	NE	NE	-	-	-	-
21	2-Methyl—3-ethylheptane	-	-	-	-	-	-	NE	NE	-	-	-	-
		-											
22	2,5,5-Trimethylheptane	-	-	-	-	-	-	NE	NE	-	-	-	-
23	4,6-Dimethyldodecane	-	-	-	-	-	-	NE	NE	-	-	-	-
24	Hendecane	-	-	-	-	-	-	NE	NE	-	-	-	-
25	n-Cetane	-	-	-	-	-	-	NE	NE	-	-	-	-
26	Tetradecane	-	-	-	-	-	-	NE	NE	-	-	-	-
27	Trioxane	-	-	-	-	-	-	NE	NE	-	-	-	-
28	Naphthalene	-	-	-	-	-	-	3.00	1.20E—04	-	-	-	-
29	Benzaldehyde	-	-	-	-	-	-	50.0	2.00E—06	-	-	-	-
30	1-Methylnaphthalene	-	-	-	-	-	-	NE	NE	-	-	-	-
31	Benzenemethanol	-	-	-	-	-	-	NE	NE	-	-	-	-
(c) CCs													
32	Formaldehyde	1.76	7.90	2.16	11.5	0.18	0.33	9.80	1.30E—05	0.02	0.03	2.29E—06	4.28E—06
33	Acetaldehyde	2.96	-	5.33	-	0.43	-	14.0	2.20E—06	-	-	-	-
34	Acrolein	-	-	-	-	-	-	0.02	NE	-	-	-	-
35	Acetone	3.63	8.73	8.65	23.1	0.71	0.66	31,000	4.00E—06	0.00	0.00	2.82E—06	2.64E—06
36	Propionaldehyde	0.56	0.60	1.70	1.82	0.14	0.05	8.00	5.00E—06	0.02	0.01	6.93E—07	2.60E—07
37	Crotonaldehyde	-	-	-	-	-	-	NE	NE	-	-	-	-
38	Butyraldehyde	0.95	-	4.90	-	0.40	-	NE	NE	-	-	-	-
39	Benzaldehyde	1.51	2.66	6.56	11.6	0.53	0.33	50.0	2.00E—06	0.01	0.01	1.07E—06	6.63E—07
40	Isovaleraldehyd	1.32	-	4.34	-	0.35	-	NE	NE	-	-	-	-
41	Valeraldehyde	1.12	-	4.68	-	0.38	-	NE	NE	-	-	-	-

*The symbol '–' indicates that the compound was either not measured, was below the detection limit, or was not applicable for the corresponding parameter calculation.

[a] In this study, the condition at T_0 was used to represent EC_i (exposure concentration in a smoking workplace), while T_1 corresponded to EC_d, representing data collected from a closed environment where a single cigarette was smoked. These values were selected as representative exposure scenarios for analysis.

[b] The Reference Concentration (RfC) refers to the maximum safe air concentration determined based on toxicological studies and regulatory guidelines, such as those established by the U.S. Environmental Protection Agency (USEPA).

[c] The Inhalation Unit Risk (IUR) represents the cancer risk per unit air concentration and is widely used in regulatory frameworks like the USEPA IRIS.

[d] 'Not established' indicates the absence of available RfC or IUR values due to insufficient toxicological data.

carbonyl compounds from HNB cigarette smoke and their associated health impact. Beyond smoking, the study also evaluated the significant role of everyday cooking in indoor air pollution. A direct comparative analysis with cooking emissions is expected to provide valuable context, highlighting how diverse sources contribute to the overall burden of indoor air pollution. These findings illustrate the broader context of indoor air quality, where routine household practices can contribute substantially to pollutant exposure. In summary, while HNB cigarettes may pose lower risks than conventional cigarettes, they are not risk free. The significant emissions from cooking further underscore the need for holistic indoor air quality management that considers multiple sources of pollution and emphasizes effective ventilation strategies.

CRediT authorship contribution statement

Hubdar Ali Maitlo: Writing – review & editing, Validation, Formal analysis. **Dae-Hwan Lim:** Writing – review & editing, Validation, Formal analysis. **Yong-Seong Lee:** Writing – original draft,

Investigation, Data curation, Conceptualization. **Ki-Hyun Kim:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Conceptualization.

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Novelty Statement

This study is the first to conduct a detailed, multi-scenario assessment of VOC emissions from heat-not-burn (HNB) cigarettes under real-use conditions. By analyzing both total and subgroup VOC concentrations across varying doses, ventilation scenarios, and time intervals, the work offers a comparative perspective against conventional cigarettes and indoor activities. The findings provide new insight into the emission dynamics of HNB products and their relative impact on indoor air quality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2025.138790.

Data availability

Data will be made available on request.

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