Science of the Total Environment 760 (2021) 143423

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Impacts of electronic cigarettes usage on air quality of vape shops and their nearby areas

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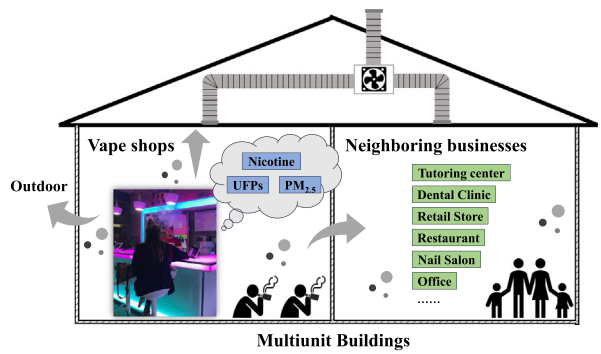
HIGHLIGHTS

- Air pollutants were measured concurrently in vape shops and neighboring businesses.
- Nicotine was detected in all the studied vape shops and neighboring businesses.
- Exhaled e-cig aerosols can transfer to nearby spaces in multiunit buildings.
- Ultrafine particles were more likely to transport to the outdoor environment.
- Door open or close largely affected the air pollution levels in the nearby areas.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 August 2020
Received in revised form 10 October 2020
Accepted 27 October 2020
Available online 1 November 2020

Editor: Philip K. Hopke

Keywords:
Vape shop
E-cigarette
Secondhand exposure
Particulate matter
Nicotine
Multiunit

ABSTRACT

With the rapid growth of the electronic cigarette (e-cig) market, there is an increasing number of vape shops that exclusively sell e-cigs. The use of e-cigs in the vape shop is a primary source of indoor particles, which might transport to its nearby indoor spaces in the multiunit setting. In this study, six pairs of vape shops and neighboring businesses in Southern California were recruited for real-time measurements of particulate pollutants between February 2017 and October 2019. The mean (SD) particle number concentration (PNC) and $PM_{2.5}$ concentration in the studied vape shops were 2.8×10^4 (2.3×10^4) particles/cm^3 and 276 (546) μg/m^3, which were substantially higher than those in neighboring businesses and outdoor areas. In addition, 24-h time-weighted average (TWA) nicotine sampling was conducted in the six pairs and three additional pairs. Nicotine was detected in the air of all the studied vape shops and neighboring businesses, in which the mean (SD) concentration was 2.59 (1.02) and 0.17 (0.13) μg/m^3, respectively. Inside vape shops, the dilution-corrected vaping density (puffs/h/100 m^3) is a strong predictor of the particle concentration, and nicotine concentration highly depends on the air exchange rate (AER). Out of the six studied pairs, PNCs in five vape shops and $PM_{2.5}$ in two vape shops were significantly correlated with those in their neighboring businesses. This correlation was stronger when the door of the vape shop was closed. When the door was open, environmental electronic vaping (EEV) aerosols, especially smaller particles, could transport from the vape shop to the outdoor environment. Overall, e-cig usage in the vape shop impacts both its own and nearby air quality, raising concerns regarding the risk of exposure to EEV aerosols in the surrounding environments.

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1. Introduction

An electronic cigarette (e-cig), belonging to the group of electronic alternatives to tobacco cigarettes (EATCs) (Protano et al., 2020), is a

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https://doi.org/10.1016/j.scitotenv.2020.143423
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battery-powered nicotine delivery system that generates aerosols by vaporizing e-liquids. Widely serving as an alternative to smoking tobacco cigarettes, the use of e-cigs (also known as vaping) has grown exponentially worldwide (Hammond et al., 2020; Yoong et al., 2018). In addition, there has been a high demand for flavored e-cig products among never-smoking adolescents and young adults since e-cigs were introduced (Glantz and Bareham, 2018; McMillen et al., 2019; Vallone et al., 2020). With the rapid growth of the e-cig markets, various e-cig devices, ranging from the disposable cigalike to a more advanced tank style and the emerging pod-based JUUL with thousands of appealing flavors, have been introduced to the public (Galstyan et al., 2019; Glantz and Bareham, 2018; Huang et al., 2019; McKelvey et al., 2018). As a result, a new type of retailer, the vape shop, where customers can exclusively purchase e-cig products and sample e-liquids with a combination of flavors and varying levels of nicotine, has emerged (Galstyan et al., 2019; Lee et al., 2018). In the United States, the growing vape shop industry accounts for 20% of the e-cig retail markets in 2019 and has proliferated globally over the past few years (Galstyan et al., 2019; Sussman et al., 2016; Truth Initiative, 2019). While many states have established smoking bans in workplaces and public spaces, the use of e-cigs is unrestricted in vape shops. Exposure to the visible massive "clouds" produced in vape shops brings an environmental and public health concern (Nguyen et al., 2019).

At the end of 2019, many cases and deaths of e-cigarette or vaping product use-associated lung injury (EVALI) have been reported in the United States (Carlos et al., 2019; Layden et al., 2019), suggesting the potential serious health risks of vaping. Using e-cigs may not only pose health harms to active users but also bystanders who are involuntarily exposed to environmental electronic vaping (EEV) aerosols (Protano et al., 2018). Although the information on the health effects of exposure to EEV aerosols is limited, a review article summarizing more than 20 studies on secondhand exposure has shown that vaping degrades indoor air quality by generating high levels of particles that are comparable to other tobacco products (Li et al., 2020b). Many studies have reported that the average fine particulate matter ($PM_{2.5}$) during active vaping in the indoor environments are mostly greater than 150 μg/m^3 and can even reach 1.5×10^3 μg/m^3 (Czogala et al., 2014; Melstrom et al., 2017; Nguyen et al., 2019; Protano et al., 2018; Protano et al., 2020; Schober et al., 2014; Son et al., 2020; Soule et al., 2017; Volesky et al., 2018; Zhao et al., 2017). The average indoor particle number concentrations (PNCs), an approximate measure for ultrafine particles (UFPs), ranged from 7.2×10^3 to 6.2×10^4 particles/cm^3 (Melstrom et al., 2017; Nguyen et al., 2019; Schober et al., 2014; Scungio et al., 2018; Volesky et al., 2018; Zhao et al., 2017). Additionally, substantial amounts of propylene glycol, vegetable glycerin, and nicotine, as well as relatively low levels of toxic compounds such as carbonyls, aromatic volatile organic compounds (VOCs), and heavy metals, have been observed in EEV aerosols in indoor environments (Li et al., 2020b). In addition to the secondhand exposure, the deposited residuals from vaping might be reemitted into the gas phase and serve as a potential source of thirdhand exposure (Goniewicz and Lee, 2015; Khachatoorian et al., 2019). The health effects of thirdhand exposure are understudied which warrant future research.

Different from typical laboratory studies in which volunteers vape an e-cig following a standard puffing protocol for a short period, continuous vaping by multiple e-cig users occurs in vape shops during business hours. Nguyen et al. (2019) found that the PNC and $PM_{2.5}$ in vape shops fluctuated dramatically and can even reach up to 4.8×10^5 particles/cm^3 and 37,500 μg/m^3, respectively. The exhaled particles can persist and mix in the indoor environment, leading to elevated concentrations at distances greater than 3.6 m away from the vaping sources (Nguyen et al., 2019). Because vape shops are typically located in multiunit buildings with at least one neighboring business, such as an office, restaurant, retail store, or clinic, the EEV particles may also travel to their neighboring businesses (Nguyen et al., 2019). Additionally, vape shops were found disproportionately located in proximity to vulnerable communities such as the low-income, minority, and youth (Berg, 2018). Vulnerable individuals who are bystanders in a vape shop or neighboring the vape shops can be at increased risks of exposure to EEV aerosols.

It has been well established that secondhand smoke (SHS) can transfer from smoking units to smoke-free adjacent units through shared ventilation, open windows, holes in walls, hallways, and electric outlets (Bohac et al., 2011; Hood et al., 2014; King et al., 2010; Russo et al., 2015). Analogous to SHS, these transfer mechanisms might also be applicable to EEV aerosols. Khachatoorian et al. (2019) detected tobacco-specific residues, including nicotine, minor alkaloids, and TSNAs, on surfaces in an indoor space adjacent to a vape shop, suggesting potential thirdhand exposures to e-cig emissions. In a laboratory setting, Zhang et al. (2020) found that the EEV aerosols transferred from a vaping room to its adjacent non-vaping room, which could be effectively reduced by blocking the door between the two rooms. However, no study has assessed the transport of EEV aerosol from vape shops to neighboring units in multiunit commercial buildings. Therefore, the aim of this study was to (1) assess the impacts of e-cig usage in vape shops on the indoor air quality of neighboring businesses, (2) identify major factors that influence the behaviors of EEV aerosols, and (3) evaluate the transport of EEV particles from the vape shop to its outdoor environment.

2. Materials and methods

2.1. Study sites

Both vape shops and their neighboring businesses in Southern California were recruited via phone calls, site visits, and brochure postings. Vape shops for this study were identified from a Yelp.com search using the keywords "vape shops". For each selected vape shop, a neighboring business was identified through the Google Maps search and site visits. The selection criteria for each pair (i.e., vape shop and its neighboring business) include: (a) The pair was adjacent to each other on the same floor in a multiunit commercial building; (b) no other tobacco products other than e-cigs were used in the vape shops; and (c) neighboring businesses were smoke-free indoor spaces. Because high levels of particles have been reported in restaurants serving barbecued, boiling, and pan-fried food (Lee et al., 2001), these restaurants were excluded in this study. A total of nine pairs of vape shops and neighboring businesses (pair IDs A–I) agreed to participate in this study.

The characteristics of the study sites such as building location, shop volume, ventilation type, air exchange rate (AER), and vaping density for each pair are summarized in Table 1 (see Supplementary Table S1 for ventilation and sampling details). All of the studied pairs A-I were located in multiunit commercial buildings, which were either in a plaza or storefront along a street. No e-cigs or other tobacco products were consumed in the studied neighboring businesses due to the smoking ban in all enclosed workplaces in California (AB-13, enacted as California Labor Code LC 6404.5). However, the smoking ban did not apply to vape shops.

2.2. Sampling protocol

Air samplings in each pair of vape shops and neighboring businesses were conducted for 3–4 days between February 2017 and October 2019. Fig. 1 illustrates the sampling types and sampling locations in the study site: (a) Sampling location 1: inside the vape shop within 1.2 m away from the vaping bar which was the main vaping activity area, (b) sampling location 2: inside the neighboring business, (c) sampling location 3: outside of the vape shop about 1–3 m away from the front door of vape shop, and (d) an additional sampling location 4 for vape shop I only: outdoor about 6–8 m away from the front door of vape shop. Real-time PNC and $PM_{2.5}$ mass concentrations were monitored concurrently in pairs A-F at sampling locations 1–3. No particle sample was collected concurrently in pairs G-I because we were not able to install the

Table 1
Characteristics and nicotine concentrations of the nine studied vape shops and their neighboring businesses.

Pairs ID[a]	Location	Vape shop					Neighboring business				Nicotine transfer[c] (%)
		Volume (m^3)	Ventilation type	AER (h^{-1})	[b]Vaping density (puffs/h/100 m^3)	24-h TWA nicotine ($\mu g/m^3$)	Volume (m^3)	Ventilation type	AER (h^{-1})	24-h TWA nicotine ($\mu g/m^3$)	
A	Plaza	168	Natural ventilation	0.29	13 (14)	3.43 (1.21)	>400	Rooftop A/C and natural ventilation	0.21	0.09 (0.04)	2.7
B	Plaza	242	Natural ventilation	0.21	13 (12)	3.08 (0.69)	>400	Rooftop A/C	0.17	0.37 (0.32)	12
C	Plaza	217	Window A/C	0.39	11 (8)	1.72 (0.51)	278	Rooftop A/C with an exhaust fan	0.60	0.42 (0.14)	24.7
D	Plaza	323	Rooftop A/C with a mixing fan	0.20	8 (4)	3.99 (1.07)	357	Rooftop A/C with mixing fans	0.20	0.13 (0.05)	3.4
E	Storefront	418	Rooftop A/C	0.22	5 (8)	3.15 (2.67)	181	Rooftop A/C	0.21	0.11 (0.04)	3.6
F	Storefront	361	Rooftop A/C	0.81	5 (6)	1.89 (1.27)	358	Rooftop A/C	0.78	0.14 (0.05)	7.5
G	Storefront	212	Rooftop A/C	1.06	NA[d]	0.65 (0.35)	160	Natural Ventilation	NA	0.09 (0.04)	13.2
H	Plaza	402	Rooftop A/C	0.31	NA	2.72 (0.26)	376	Rooftop A/C	0.58	0.07 (0.05)	2.6
I	Plaza	260	Rooftop A/C or natural ventilation	0.24	20 (6)	2.71 (1.50)	116	Rooftop A/C	0.30	0.06 (0.03)	2.4

Abbreviations: AER, air exchange rate; A/C, air conditioning; TWA, time-weighted average; NA, not applicable.
[a] Real-time particle samplings were conducted in pairs A–F while nicotine samplings were conducted in all nine pairs.
[b] Vaping density (puffs/h/100 m^3): total number of puffs per hour normalized by the shop volume for each vape shop.
[c] Nicotine transfer: the percentage of nicotine transferred from vape shop to neighboring business = (neighboring business nicotine concentration / vape shop nicotine concentration) × 100%.
[d] NA due to lack of access.

particle sampling instruments in the neighboring businesses. The transport of EEV particles from the vape shop to its outdoor area was investigated in vape shop I at sampling locations 1, 3, and 4 when the door of vape shop I was open. Particle size distributions were measured inside pair B (sampling locations 1 and 2) and vape shop C (sampling location 1 only). The 24-h time-weighted average (TWA) airborne nicotine samplings were conducted in all pairs A-I at sampling locations 1 and 2.

On each sampling day, particle monitoring was conducted for about 5–8 h during overlapping business hours between a vape shop and its neighboring business. Observation notes were recorded by research staff who stayed in the vape shop during the 5–8 sampling hours including (1) characteristic information such as shop volume (m^3), ventilation type, and location; (2) total number of puffs generated by e-cig users including customers and employees in the vape shops every minute, which allowed us to calculate the total number of puffs per unit time; (3) any changes of ventilation settings such as opening or closing the shop doors and A/C switching on or off; and (4) activities with any potential particle emissions.

2.3. Measurement of particle number, $PM_{2.5}$, and particle size distribution

Three sets of instruments were installed at sampling locations 1–3 to measure real-time PNC and $PM_{2.5}$ mass concentration simultaneously. At each sampling location, a portable Condensation Particle Counter

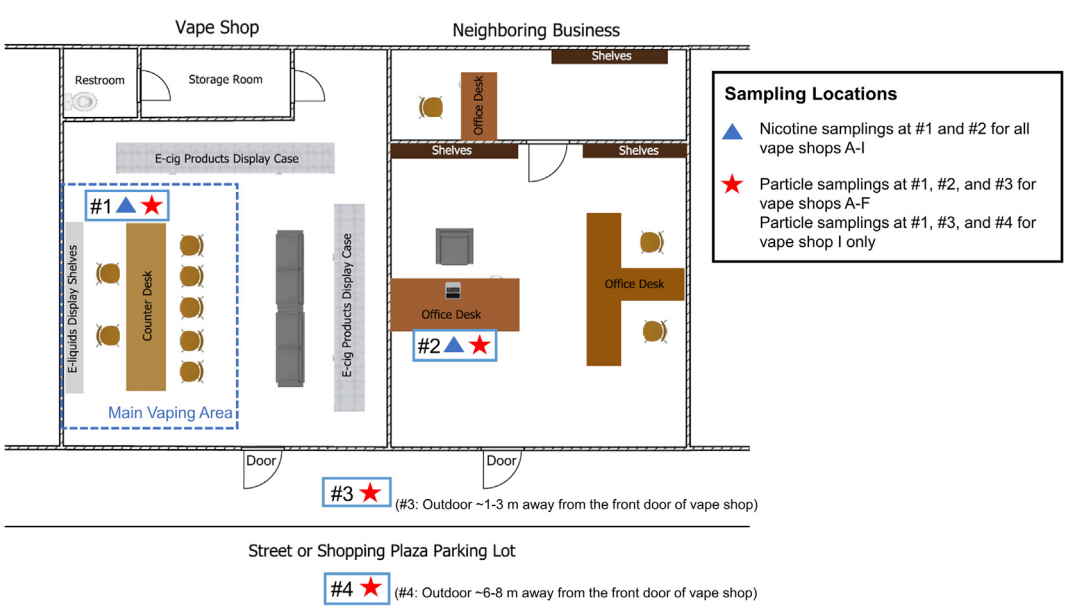

Fig. 1. The schematic diagram of sampling types and sampling locations in a representative pair of vape shop and its neighboring business.

(CPC 3007, TSI Inc., Shoreview, MN) or a DiSCmini (Diffusion Size Classifier Miniature, Testo SE & Co. KGaA, Germany) and a DustTrak II Aerosol Monitor (DustTrak II 8532, TSI Inc.) were used to measure PNC and $PM_{2.5}$, respectively, at 2-min logging intervals. Real-time carbon dioxide (CO_2) concentrations, temperature, and relative humidity were measured at 1-minute intervals by two indoor air quality monitors (Q-Trak 7575, TSI Inc.) in vape shops and neighboring businesses. Using the CO_2 concentration data, we calculated the room AER by the CO_2 tracer gas decay method (Batterman, 2017; Nguyen et al., 2019). In addition, particle size distributions in the size range of 7–289 nm and 0.5–19.8 μm were measured in pair B and vape shop C with a Scanning Mobility Particle Sizer (SMPS 3080, TSI Inc.) (100 s up scan, 20 s down scan) and Aerodynamic Particle Sizer (APS 3321, TSI Inc.), respectively.

2.4. Measurement of airborne nicotine concentrations

Airborne nicotine was collected using a modified sampling method (Chen et al., 2017; Lopez et al., 2013) that was first developed by Hammond and Leaderer (1987). The sampler with a 37 mm filter pretreated with sodium bisulfate was connected to a pump at a sampling rate of 3 L/min. The sampling flow rate were verified by a mass flow meter (Model 4140, TSI Inc.) at the start and end of each sampling session. The average flow rate of the two values was used to calculate the total air volume. The active nicotine samplers were installed at sampling locations 1 and 2 in each pair for a period of 24 h. A total of 3–5 nicotine samples were collected in each pair. To ensure nicotine data quality, an outdoor sample for each pair of shops was also collected. All the nicotine filters were extracted using dichloromethane with an internal standard (i.e., 2 μg/mL quinoline) and analyzed by gas chromatography–mass spectrometry (GC–MS). The limit of quantification (LOQ) of GC–MS was 0.2 μg per filter, equivalent to 0.05 μg/m^3 24-h TWA nicotine. The TWA airborne nicotine concentration was calculated by dividing the total mass of nicotine collected in the filter by the product of flow rate (i.e., 3 L/min) and sampling time in minutes.

2.5. Quality control/quality assurance for data collection and analysis

Before each sampling session, particle sampling instruments were zero checked and collocated for at least 30 min for quality assurance. Regression results from the collocation tests have been applied to correct all the PNC and $PM_{2.5}$ data throughout this study.

DustTrak is sensitive to the composition and size distribution of airborne particles leading to notable upward $PM_{2.5}$ bias during air sampling (Moosmuller et al., 2001; Zhao et al., 2017). Therefore, we have conducted gravimetric calibration of DustTrak II $PM_{2.5}$ measurements in this study. The detailed process has been described previously (Nguyen et al., 2019; Zhao et al., 2017). Briefly, $PM_{2.5}$ gravimetric samples were collected using personal cascade impactors side by side with the DustTrak II inside selected vape shops and outdoor sampling locations. A calibration factor of 0.25 ± 0.009 ($R^2 = 0.95$; 95% CI, 0.22 to 0.28) and 0.48 ± 0.026 ($R^2 = 0.98$; 95% CI, 0.41 to 0.55) was determined for $PM_{2.5}$ data in vape shop and ambient sampling locations (i.e., outdoor and neighboring business), respectively, from gravimetric analysis.

2.6. Data analysis

The arithmetic mean and standard deviation (SD), as well as median and interquartile range (IQR), of PNC, $PM_{2.5}$, and nicotine concentrations were calculated for each pair of vape shops and neighboring businesses during overlapping business hours. Kruskal-Wallis ANOVA on Ranks was used to compare e-cig-related air pollutant levels in vape shop with neighboring business and outdoor sampling locations. In an effort to examine the temporal dynamics of particle transfer, linear regression analyses were used to determine the correlation between particle concentrations in vape shops and vaping-free areas (i.e., neighboring businesses or outdoor sampling locations) using 10-min averaged data. Based on field observation notes, vaping density (puffs/h/100 m^3), defined as the total number of puffs per hour normalized by the shop volume, for each vape shop was estimated. The effects of parameters such as AER and vaping density on the e-cig-related air pollutant levels in vape shops were also assessed by linear regression. Hourly averaged data were used to investigate the effects of vaping density on particle concentrations.

R 3.4.0 and Microsoft Excel 2016 (Microsoft, Seattle, WA, USA) were used to summarize data and perform statistical analyses. All figures were generated with Sigmaplot 14.0 (Systat Software Inc., San Jose, CA). The level of statistical significance was set at $p < 0.05$.

3. Results and discussion

3.1. E-cig related air pollutants in the vape shops and neighboring businesses

3.1.1. Particle concentrations

The PNC and $PM_{2.5}$ concentrations for pairs A–F during overlapping business hours are presented with respect to mean vaping density in Fig. 2 (see Supplementary Table S2 and Table S3 for the mean and

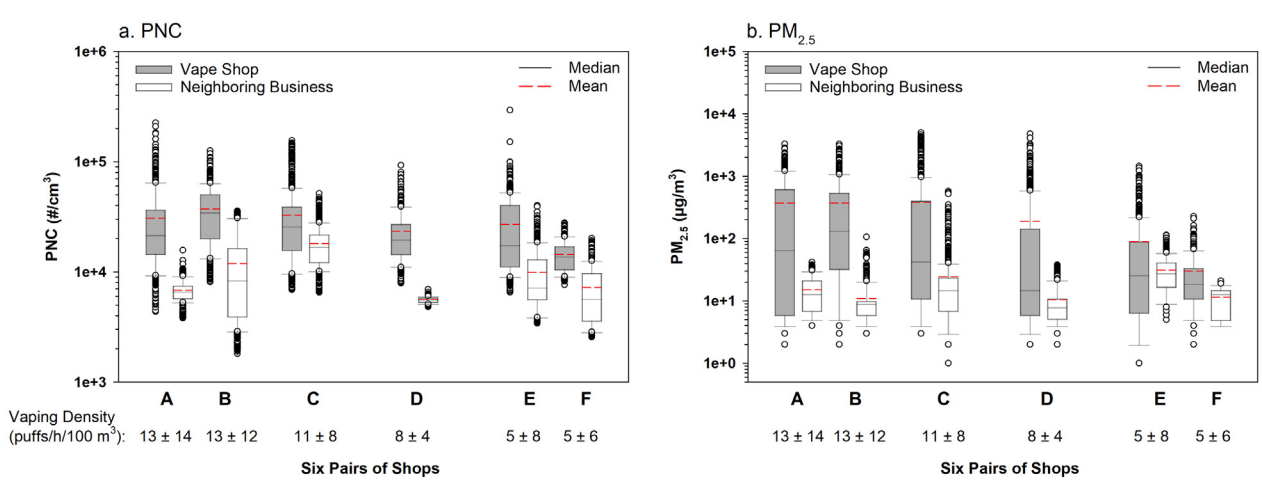

Fig. 2. Box plots summarizing (a) PNC and (b) $PM_{2.5}$ mass concentrations measured during all sampling sessions for the six pairs of vape shops and neighboring businesses A–F by vaping density. The solid line in each box represents the median value, and the dash line in each box represents the mean value.

median particle concentrations, respectively). The median (IQR) PNCs in the six vape shops during the sampling sessions ranged from 1.4×10^4 (1.1×10^4, 1.7×10^4) to 3.5×10^4 (2.0×10^4, 5.0×10^4) particles/cm^3. For $PM_{2.5}$, the median (IQR) concentration was within the range of 15 (6, 145)–134 (33, 541) μg/m^3. Both PNC and $PM_{2.5}$ observed in vape shops were at the comparable level to a previous vape shop study (Nguyen et al., 2019). When customers were at high volumes, the peak PNCs and $PM_{2.5}$ concentrations in the vape shop can even reach 2.9×10^5 particles/cm^3 and 4988 μg/m^3, respectively. As the vaping density decreased from 13 to 5 puffs/h/100 m^3, the mean $PM_{2.5}$ in the vape shops A-F significantly decreased ($r = 0.97$, $p = 0.002$). A similar but less prominent trend was observed for PNCs ($r = 0.81$, $p < 0.05$). As to the median concentrations, however, there is no significant correlation detected. It should be noted that vape shops A and B enhanced their natural ventilation by opening their shop doors only for 18% and 20% of sampling time, respectively, but did not use any ventilation for most of the time (Table S1).

The PNC and $PM_{2.5}$ in vape shops A-F were significantly higher than their neighboring businesses (Kruskal-Wallis, $p < 0.001$), except for $PM_{2.5}$ in vape shop E. The mean (SD) PNCs in the neighboring businesses reached up to 1.8×10^4 (7.3×10^3) particles/cm^3 which was higher than most of the common indoor environments such as homes, offices, and schools (Morawska et al., 2017). The mean $PM_{2.5}$ concentrations in neighboring businesses A, C, and E exceeded the U.S. Environmental Protection Agency's annual standard of 12 μg/m^3, which is the maximum allowable concentration for outdoor air quality (U.S. Environmental Protection Agency, 2016). Although there is currently no standard for $PM_{2.5}$ in the indoor environments, the indoor $PM_{2.5}$ levels are expected to be the same as, or lower than, outdoor levels when there is no other indoor emission source (U.S. Environmental Protection Agency, 2020).

On the other hand, PNC and $PM_{2.5}$ in vape shops A-F were all significantly greater than those measured at outdoor sampling locations (Kruskal-Wallis, $p < 0.001$; see Supplementary Table S2), suggesting that the high concentration measured in vape shops were not due to outdoor impacts such as vehicular emissions.

3.1.2. Airborne nicotine concentration

Gas-phase nicotine, as a tracer for EEV aerosols, was detected in all nine pairs, suggesting EEV aerosol transfer from vape shops to neighboring businesses (Table 1). The median (IQR) concentration of the 24-h TWA nicotine measured in vape shops and neighboring businesses were 2.72 (1.80, 3.29) μg/m^3 and 0.11 (0.08, 0.26) μg/m^3, respectively. The nicotine levels estimated in the vape shops were comparable to previous studies that recruited volunteers to use e-cigs in a room (0.20–6.23 μg/m^3) (Czogala et al., 2014; Geiss et al., 2015; Johnson et al., 2018; Liu et al., 2017; Melstrom et al., 2017; Schober et al., 2014). The nicotine levels in vape shops were found to be similar to those in smoking hospitality venues in Ghana where nicotine samples were passively collected for 7 days (Agbenyikey et al., 2011). However, the nicotine levels in vape shops were about 5–10 times lower than those measured in smoking allowed restaurants and bars where nicotine samples were collected during 4 busy hours (Bolte et al., 2008). The nicotine levels in all the studied vape shops and four of the neighboring businesses were significantly higher than those at e-cig users' homes (0.11 μg/m^3) (Ballbè et al., 2014). On the other hand, Chen et al. (2017) reported an exceptionally high nicotine concentration ~ 125 μg/m^3 at a vaping convention with more than 1000 participants in a 13,475 m^3 venue (i.e., 13 m^3 per person or 7 occupants per 100 m^3). In the current study, there were usually 2–7 people inside vape shops (i.e., ~41–145 m^3 per person or ~1–2 occupants per 100 m^3) during our sampling time. Therefore, the difference in nicotine concentration may be explained by two factors: (1) the space occupied by each person in the vaping convention is lower than that in vape shops, suggesting less dilution for EEV aerosols; (2) our sampling inside vape shops included overnight periods when there was no vaping; in contrast, sampling in the vaping convention was conducted only during active vaping periods. Nevertheless, Johnson et al. (2018) reported a low median concentration of nicotine ~1.1 μg/m^3 in four e-cig vaping events where the occupancy densities were ~17–200 m^3 per person (1–6 occupants per 100 m^3), which were closer to what observed in the vape shops.

Similar to previous e-cig indoor studies (Ballbè et al., 2014; Chen et al., 2017; Johnson et al., 2018), our method only measured gas-phase not particulate phase nicotine. To understand the total exposure to nicotine from EEV aerosols, the gas/particle partitioning of nicotine should be considered in future studies. Assuming the nicotine measured in the neighboring business was all from its adjacent vape shop, the percentage of nicotine transfer ranged from 2.4 to 24.7%. Although the airborne nicotine levels varied depending on the level of nicotine in the e-liquids selected by e-cig users as well as the customer traffic, the identification of nicotine in all studied vape shops and neighboring businesses confirmed that involuntary exposures to EEV aerosols occurred in these indoor environments.

3.2. Predictors of air pollutants concentrations inside vape shops

A previous study (Nguyen et al., 2019) used the total number of puffs every 30 min as a predictor which had strong correlation with both PNC ($r = 0.74$, $p < 0.001$) and $PM_{2.5}$ concentrations ($r = 0.75$, $p < 0.001$) in vape shops when the shop door was closed. After considering the different vape shop volumes, we found that the dilution-corrected vaping density (puffs/h/100 m^3) had an even stronger positive correlation with PNC ($r = 0.82$, $p < 0.001$) and $PM_{2.5}$ ($r = 0.88$, $p < 0.001$), respectively (Fig. 3). This result is in agreement with recent findings that EEV aerosols can be substantially affected by the dilution condition (Floyd et al., 2018; Ingebrethsen et al., 2012; Meng et al., 2017; Zhao et al., 2016). Additionally, the $PM_{2.5}$ mass concentration showed a better correlation with vaping density compared to PNC, suggesting that fine particles are more sensitive to dilution compared to smaller particles.

In addition to vaping density, we previously found that lower AERs in vape shops could increase the particle levels measured from opening to closing of business on busy days (Nguyen et al., 2019). In this study, all of the studied vape shops and neighboring businesses did not use any central ventilation during sampling sessions. Only either A/C (without outdoor air supply) or natural ventilation was observed in the shops. Accordingly, the AERs for all of the pairs ranged from 0.20 to 1.06 h^{-1}. We found a negative, significant association between the AER and 24-h TWA airborne nicotine concentration in vape shops (see Supplementary Fig. S1; $r = -0.86$, $p = 0.003$). This finding confirms that the mitigation of nicotine pollution in vape shops can be achieved by enhancing ventilation despite the varying levels of nicotine in different e-cig products. Due to a small number of studied vape shops with relatively low AERs in this study, future research is warranted to systematically evaluate the effects of ventilation on indoor airborne nicotine levels.

3.3. Impacts of EEV emissions from vape shops on nearby areas

3.3.1. Indoor air quality of neighboring businesses

The relationship between the 10-min averaged concentrations (i.e., both PNC and $PM_{2.5}$) inside vape shops and those in neighboring businesses A-F were summarized in Table 2 (see Supplementary Figs. S2 and S3 for the regression analysis). For PNCs, significant correlations ($r > 0.33$, $p < 0.001$) were detected in 5 out of 6 pairs (i.e., A, B, C, E, and F). A moderate or strong correlation ($r > 0.40$) was observed in pairs A, B, and C, which had higher vaping density compared to other pairs. The weakest correlation shown in pair E among the five pairs with significant correlations was likely because their ventilation systems were separated by a wall while the ventilation system of other pairs were connected. The slopes of the linear regression relating the PNCs in neighboring businesses to those in vape shops ranged from

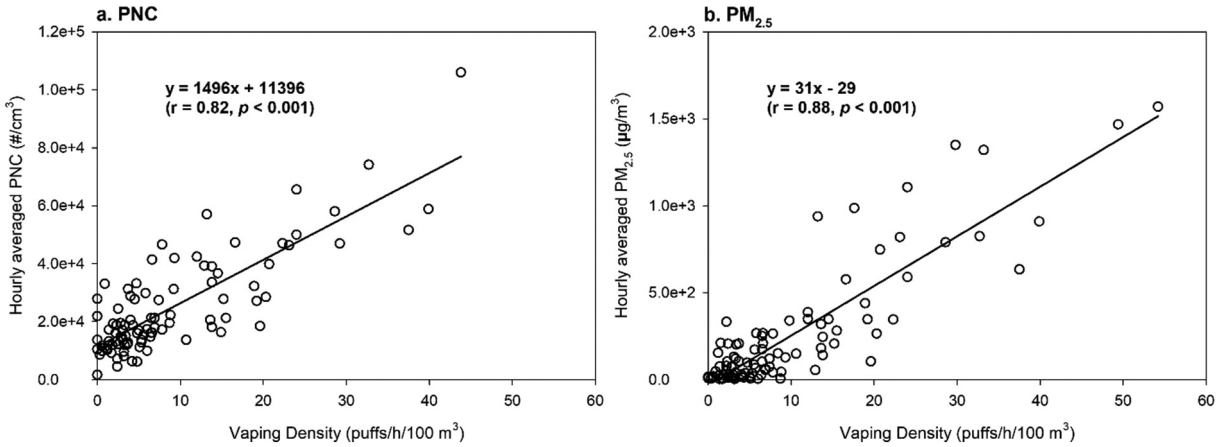

Fig. 3. Relationships between hourly averaged PNC and $PM_{2.5}$ and vaping density (puffs/h/100 m^3) when the shop door was closed for vape shops A–F and I with particle samplings.

0.035 to 0.368. In other words, PNCs in the neighboring businesses were expected to increase by 35 to 368 particles/cm^3 when the PNC in vape shops increased by 1000 particles/cm^3. Notably, the regression slopes for pairs B and F were 3–10 times higher than other pairs possibly because multiple pathways such as the ductwork in their shared ventilation systems, doors, shared walls, and building cracks contributed to the particle transfer between the two indoor spaces. Future studies are needed to identify these potential pathways in multiunit buildings for mitigation purposes. No significant correlation was observed for pair D likely because the sampling instruments were installed behind several large massage chairs in the corner of the neighboring business, creating an enclosed area in which the EEV particles could hardly reach.

Regarding $PM_{2.5}$, while the correlations were weak for most pairs, significant results ($r > 0.33$, $p < 0.001$) were observed in 2 out of 6 pairs (i.e., A and C). The regression slopes were 0.010 and 0.041 for pairs A and C, respectively. Interestingly, the correlation coefficient for $PM_{2.5}$ in pair C reached as high as 0.83, which was likely driven by the extremely high $PM_{2.5}$ levels (1000–4500 μg/m^3) in vape shop C. The reason why the transfer of UFPs in pair C is less prominent compared to $PM_{2.5}$ can be explained by the change of particle size in vape shop C (see Supplementary Fig. S4). When vaping density increased from 10 to 44 puffs/h/100 m^3, the particle mass distribution shifted from a typical single mode at 1 μm, which has been observed in previous studies (Baassiri et al., 2017; Floyd et al., 2018), to a trimodal pattern of 0.3, 0.8, and 3 μm. The increase of the micron-sized particles can be explained by the fact that the emitted UFPs coagulated with the 1 μm particles resulting in a growth of particle mass to the 3 μm mode. Mikheev et al. (2016) and Floyd et al. (2018) have demonstrated that coagulation effectively increases the e-cig particle mass while depleting smaller particles. As a result, the increase of PNC (from 2.3×10^4 to 2.8×10^4 particles/cm^3) was less prominent than $PM_{2.5}$ which surged by 6 times to 127 μg/m^3 in the neighboring business when emission increased in vape shop C. These results show that both UFPs and $PM_{2.5}$ from the vape shops can impact the indoor air quality in their neighboring businesses.

The higher particle transfer rates were observed in pairs B, C, and F, which also had higher nicotine transfer rates compared to other pairs (see Table 1). The highest nicotine transfer rate (i.e., 24.7%) was observed in pair C likely because the neighboring business C experienced significant impacts of both particle number and mass on their indoor air quality. Notably, despite no significant correlation observed for particles in pair D, 3.4% of gas-phase nicotine still transferred from vape shop D to its neighboring business suggesting indoor air pollution due to vaping.

3.3.2. Outdoor air quality

As the EEV aerosols in the vape shop can transfer to its neighboring business in the multiunit building, we were also interested in whether the EEV particles can travel to the outdoor environment. The relationship between the 10-min averaged concentrations (i.e., both PNC and $PM_{2.5}$) inside and outside vape shops A-F is also summarized in Table 2 (see Supplementary Figs. S5 and S6 for the regression analysis). For PNCs, significant correlations ($r > 0.33$, $p < 0.001$) were detected only in vape shops A and B with natural ventilation. Both vape shops

Table 2
Linear regression analysis relating the 10-min averaged PNC and $PM_{2.5}$ in neighboring businesses and outdoors (sampling location 3) to those in vape shops for pairs A-F.

Vape shops	PNC			$PM_{2.5}$		
	Slope (95% CI)	p-Value	r	Slope (95% CI)	p-Value	r
Neighboring businesses						
A	0.035 (0.027, 0.043)	<0.001	0.59	0.010 (0.008, 0.013)	<0.001	0.56
B	0.316 (0.238, 0.394)	<0.001	0.62	−0.002 (−0.006, 0.002)	0.329	−0.09
C	0.136 (0.105, 0.168)	<0.001	0.55	0.041 (0.0369, 0.045)	<0.001	0.83
D	−0.008 (−0.017, 0.001)	0.075	−0.22	−0.003 (−0.006, 0.001)	0.148	−0.12
E	0.111 (0.054, 0.167)	<0.001	0.37	0.020 (−0.003, 0.042)	0.084	0.15
F	0.368 (0.119, 0.616)	0.005	0.39	0.016 (−0.044, 0.077)	0.595	0.07
Outdoors						
A	0.076 (0.043, 0.109)	<0.001	0.37	0.006 (0.005, 0.008)	<0.001	0.64
B	0.584 (0.451, 0.716)	<0.001	0.66	0.013 (−0.009, 0.034)	0.251	0.12
C	0.054 (−0.010, 0.117)	0.099	0.13	−0.000 (−0.002, 0.002)	0.937	−0.01
D	0.222 (−0.050, 0.495)	0.107	0.27	−0.001 (−0.003, 0.001)	0.428	−0.07
E	−0.056 (−0.106, −0.006)	0.030	−0.30	−0.005 (−0.011, 0.001)	0.120	−0.17
F	0.088 (−0.033, 0.210)	0.149	0.28	0.089 (0.037, 0.141)	0.001	0.43

A and B also had the highest vaping density among the six studied vape shops, which contributed to increasing the particle concentration gradient between indoors and outdoors. According to the Fick's first law of diffusion, particles might transport from vape shops to outdoor areas through the open doors and holes on the wall. The regression slope for vape shop B was 7 times higher than vape shop A possibly because of the higher vaping frequency (i.e., 46.2 puffs/h) in vape shop B when the door was open compared to vape shop A (i.e., 25.4 puffs/h). For $PM_{2.5}$, a significant correlation was only observed in vape shop A.

3.4. Effects of vape shop door open and close on particle transport

3.4.1. Neighboring businesses

The effects of door open and close on UFP transfer from a vape shop to its neighboring business for pair B are further illustrated in Fig. 4. During the sampling period, the vape shop door was closed before 14:30 except for customers walking in and out, and then kept open after 14:30. Following the PNC spikes in the vape shop, the PNC levels were also elevated in the neighboring business (Fig. 4a). Shortly following the vape shop door open, the PNC started to diminish in the neighboring business (Fig. 4a). Consequently, the mean PNC decreased by 19% to 4.3×10^4 (2.0×10^4) particles/cm^3 in the vape shop (Kruskal-Wallis, $p < 0.05$) and decreased by 33% to 1.8×10^4 (4.8×10^3) particles/cm^3 in neighboring business (Kruskal-Wallis, $p < 0.001$).

Fig. 4b and c presents the contour plots of the number-based particle size distribution for pair B. The color intensity indicates the normalized particle number concentration (dN/dLogDp) for a given particle size at a given time. As demonstrated by Nguyen et al. (2019), the particles emitted in the vape shop were characterized by a bimodal particle number distribution of 60 nm and 250 nm when the shop door was closed. Meanwhile, UFPs largely penetrated into the neighboring business showing a single mode at 60 nm. Since UFPs may deposit deep into the human lung and induce greater adverse respiratory effects (Peters et al., 1997; Sturm, 2016), the exposure to EEV related UFPs might bring more health concerns for employees and patrons in the neighboring business. Under the effect of door open, the particle size distribution in the vape shop shifted to a single mode while the UFPs started to decrease shortly after door open.

Opening and closing the vape shop doors changed the condition of ventilation in vape shops A and B. When the door of the vape shop was closed, an even stronger correlation in terms of PNC was observed for pairs A ($r = 0.62$, $p < 0.001$) and B ($r = 0.66$, $p < 0.001$). This was most likely a result of the enhanced particle concentration gradient between the vape shop and neighboring business because particles persisted and remained at high concentrations in the vape shop during door closed periods (Nguyen et al., 2019). However, no significant correlations were observed for both pairs A ($r = 0.36$, $p > 0.05$) and B ($r = 0.25$, $p > 0.05$) when their shop doors were open due to the enhanced dilution from outdoor air. For $PM_{2.5}$, a similar but less prominent

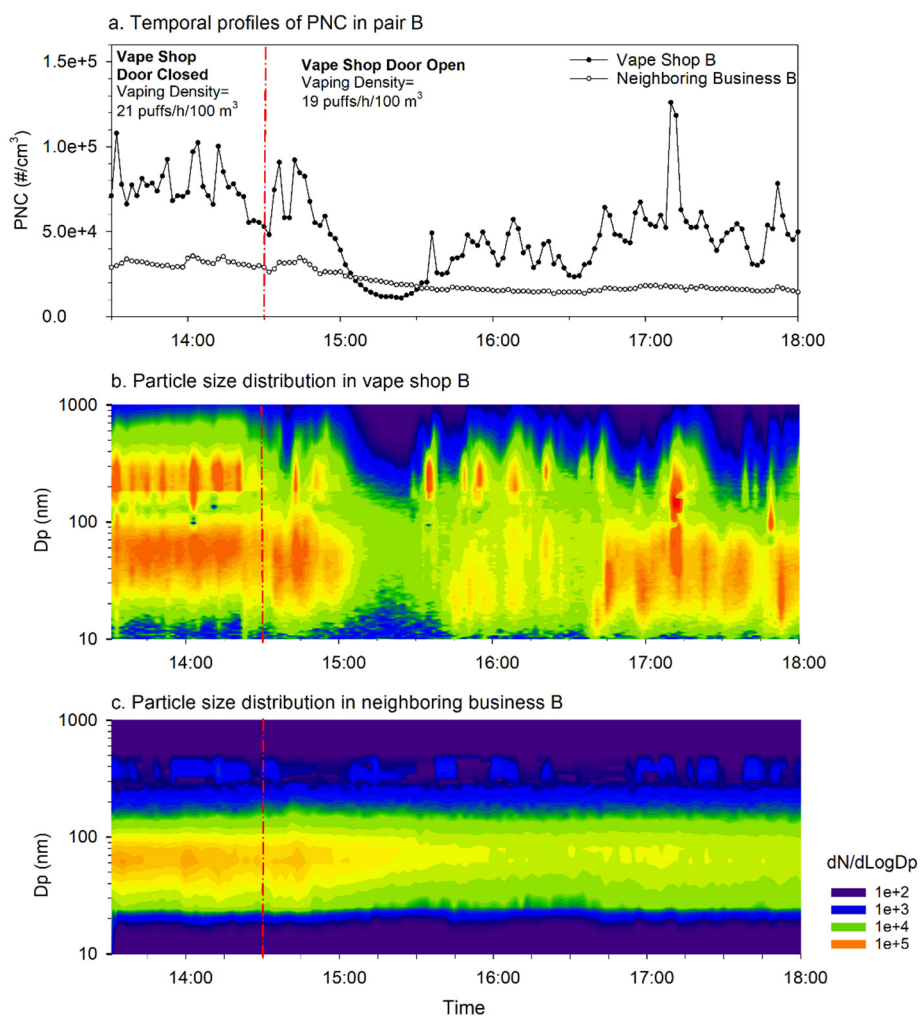

Fig. 4. Temporal profile of (a) PNC in vape shop B and its neighboring business B as well as particle size distributions in (b) vape shop B and (c) neighboring business B during overlapping business hours on a day with ventilation changes. Note: The door of vape shop was closed during 13:30–14:30 and the door was open during 14:30–18:00.

effect was observed in pair A, but no significant correlation was presented in pair B at all. Future research is warranted to systematically evaluate more mitigation strategies that would effectively reduce exposure to EEV aerosols in public multiunit buildings.

3.4.2. Outdoor environment

While opening doors significantly reduced particle levels inside vape shops and neighboring businesses, it might increase the transport of EEV particles from vape shops to outdoor areas. Indeed, as shown in Fig. 5, linear regression demonstrated that the correlation between particle concentrations (i.e., PNC and $PM_{2.5}$) inside and outside vape shop B was stronger when the shop door was open compared to that was closed. In addition, the regression slope was greater during the door open periods, suggesting particles due to vaping largely transported from vape shop to its outdoor environment, compared to the door closed. Similar results were also observed for vape shop A (see Supplementary Fig. S7). As shown in Supplementary Fig. S8, the exceptionally high ratio between the indoor and outdoor particle concentration (or I/O) demonstrated that vaping was a major indoor emission source in vape shops A and B regardless of door opening or closing. Compared to door closed periods, door opening significantly reduced the I/O ratios for both PNC and $PM_{2.5}$. Like indoor spaces with smoking cigarettes that showed $PM_{2.5}$ I/O ratio reached ~11 with the minimal AER (Li and Chen, 2003), the median I/O ratio in vape shops was up to 34 during door closed periods where the ventilation was dominated by infiltration (Chen and Zhao, 2011). After the shop door was open, the AER between indoor and outdoor likely increased, resulting in significantly lower I/O ratios around 2–4. This is because that the outdoor air with a lower particle concentration penetrated into vape shops more quickly and diluted the indoor EEV aerosols. At the same time, EEV aerosols traveled to the outdoor environment.

To further study the effect of proximity to vape shop on outdoor particle concentrations, additional particle measurements were conducted simultaneously at indoor sampling location 1 and outdoor sampling locations 3 and 4 for vape shop I (Fig. 6). As seen in Fig. 6a, the mean PNCs were 3.1×10^4, 1.3×10^4, and 8.9×10^3 particles/cm^3 at sampling locations 1, 3, and 4, respectively. When the sampling location moved from indoor location 1 to outdoor locations 3 and 4, the PNC dropped to 41% and 29% of what was measured in the vape shop, respectively. The significant correlations of location 1 with location 3 ($r = 0.51$, $p < 0.001$) and 4 ($r = 0.37$, $p = 0.004$) indicate that small particles measured by PNC transported from the vape shop to the outdoor area and could even reach ~6–8 m away from the shop.

In Fig. 6b, the mean $PM_{2.5}$ was 472, 27, and 5 μg/m^3 at sites 1, 3, and 4, respectively. When the sampling location moved to 3 and 4, $PM_{2.5}$ dropped to 6% and 1%, of what was measured in the vape shop. Compared to UFPs, the stronger correlation between locations 1 and 3 ($r = 0.75$, $p < 0.001$) observed for $PM_{2.5}$ indicates that fine particles traveled to outdoor location 3 from the vape shop despite at a low level. However, the insignificant correlation between locations 1 and 4 ($r = 0.01$, $p > 0.05$) for $PM_{2.5}$ showed that large particles hardly traveled for a long distance because EEV particle mass decreased more rapidly due to evaporation compared to particle number (Li et al., 2020a).

Previously, Zhao et al. (2017) found that only 7% of PNC and 1% of $PM_{2.5}$ remained beyond 2.5 m away from an e-cig user in an indoor environment. With more vaping events in the vape shop than a laboratory setting, our results indicate that EEV particles not only persisted in the indoor environment but also traveled to outdoor areas from the vape

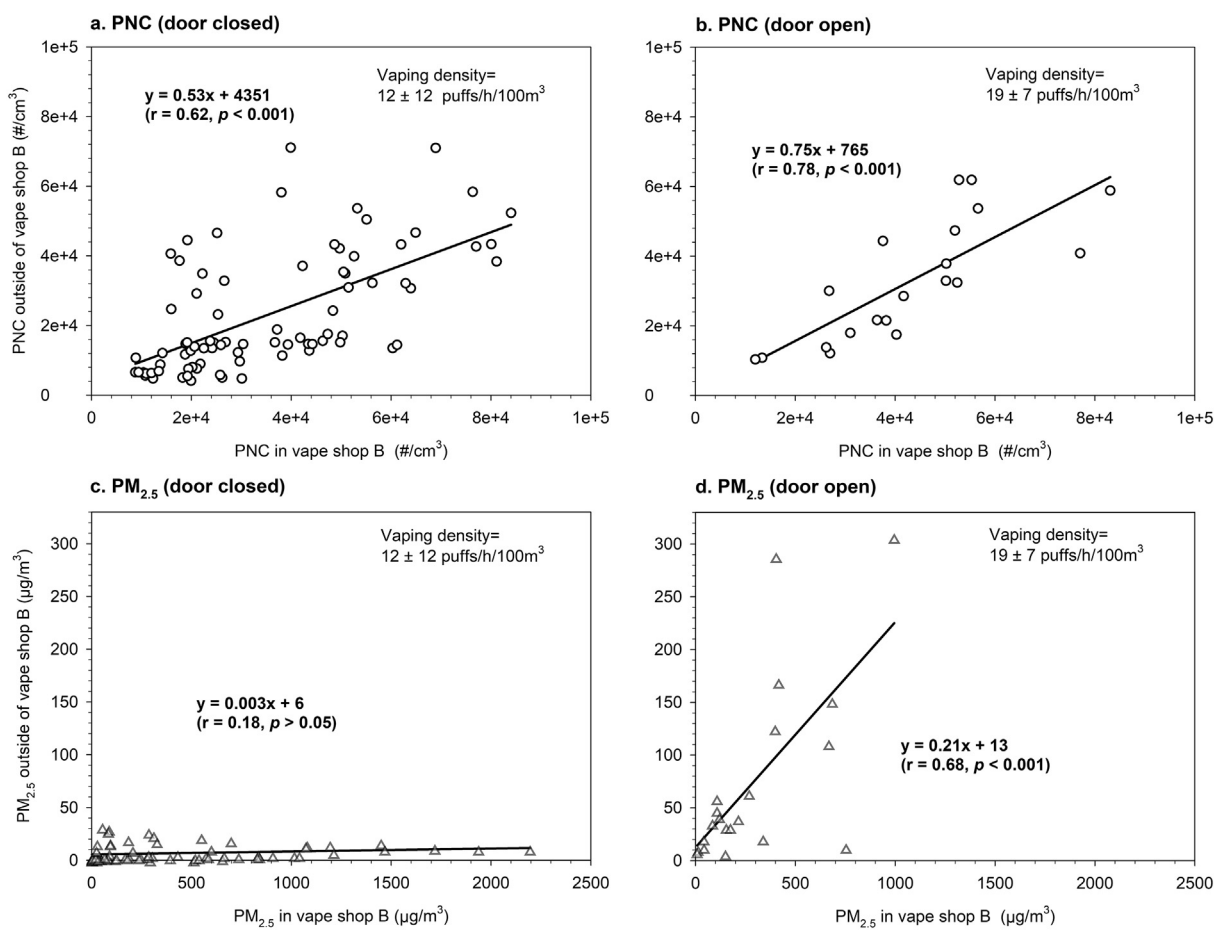

Fig. 5. Effects of door open and close on the particle transport from vape shop B to the outdoor environment (i.e., sampling location 3: ~1–3 m away from the front door of vape shop B).

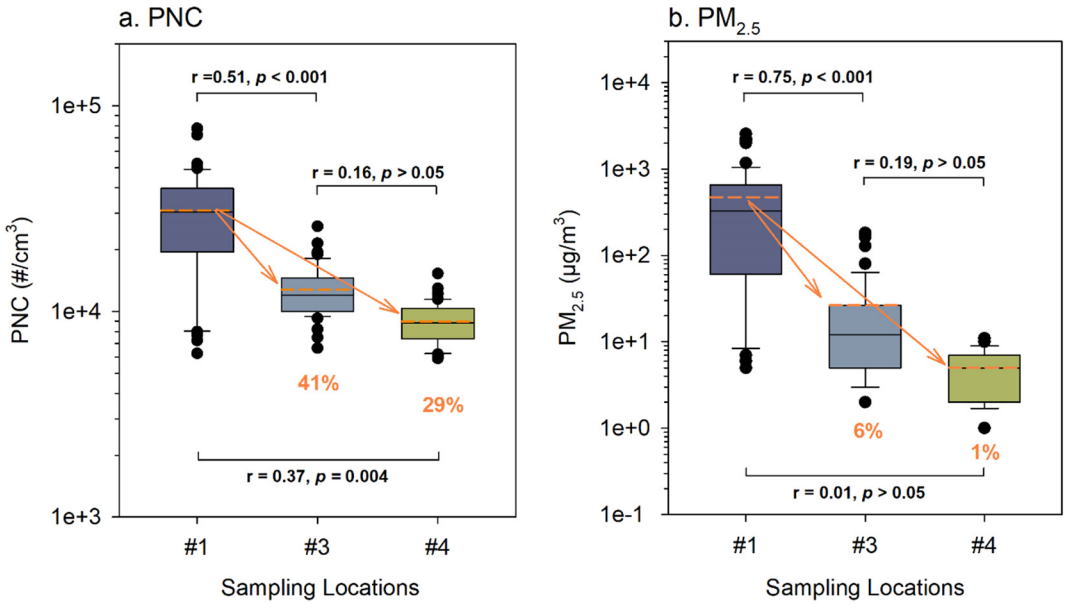

Fig. 6. (a) PNC and (b) $PM_{2.5}$ at indoor sampling locations 1 (inside vape shop) as well as outdoor sampling locations 3 (outside ~1–3 m away from the vape shop door) and 4 (outside ~6–8 m away from the vape shop door) for vape shop I. The solid line in each box represents the median value, and the dash line in each box represents the mean value.

shop, especially for small particles. Both UFPs and $PM_{2.5}$ transported from the vape shop to outdoor areas, leading to exposure risk for passersby and patrons in the shopping strip or plaza. On the other hand, EEV particles with the capability to travel farther away may enter the neighboring business through infiltration. A trade-off should be considered between using natural ventilation as the mitigation strategy to reduce exposure to EEV aerosols. However, the natural ventilation was the only method used by the studied vape shops. Other ventilation types such as mechanical ventilation with either an exhaust or supply air system should be considered in future studies.

4. Conclusions

This is the first study that focuses on the transport of EEV aerosols from vape shops to neighboring indoor spaces in multiunit buildings and the outdoor environment. The PNC and $PM_{2.5}$ concentration in the studied vape shops were substantially higher than those in neighboring businesses and outdoor areas. Gas-phase nicotine was detected in all the studied vape shops and neighboring businesses. The results of this study indicate that EEV aerosols can transfer from the vape shops to neighboring businesses. Compared to $PM_{2.5}$, UFPs are more likely to travel to nearby indoor spaces. Under the extremely high level of $PM_{2.5}$ in the vape shop, the particle mass transfer from the vape shop to a neighboring business could also occur. Opening the door of the vape shop substantially reduced the aerosol transport from the vape shop to its neighboring business. During door open periods, EEV aerosols, especially small particles, could transport from vape shop to outdoor areas. These data provide strong policy implications in terms of protecting employees, patrons, and bystanders from exposures to EEV aerosols in indoor and outdoor spaces adjacent to vape shops. Further research on mitigation measures is needed to better inform policy. The high levels of indoor air pollutants produced by using e-cigs call for precautionary measures to protect public health.

CRediT authorship contribution statement

Liqiao Li: Conceptualization, Field sampling, Data curation, Analysis, Writing. Charlene Nguyen: Field sampling, Data curation, Reviewing and Editing. Yan Lin: Methodology, Reviewing and Editing. Yuening Guo: Field sampling, Data curation. Nour Abou Fadel: Field sampling. Yifang Zhu: Conceptualization, Methodology, Supervision, Resource, Writing - reviewing and editing.

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.

Acknowledgments

This work was supported by the Tobacco-Related Disease Research Program (TRDRP) (Contract # 23XT-0001 and T29IR0480). We thank Dr. Mel Suffet and Dr. Shane Que Hee for their technical support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.143423.

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