Title

Real-time Assessment of Fine and Ultrafine Particle (UFP) Mitigation Performance with an Air Purifier at a Local Electronic Cigarette Store

Author

Lin, Che-Hsuan

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Real-time Assessment of Fine and Ultrafine Particle (UFP) Mitigation Performance with an Air Purifier at a Local Electronic Cigarette Store

A thesis submitted in partial satisfaction
of the requirements for the degrees Master of Science
in Environmental Health Sciences

by

Che-Hsuan Lin

2018

ABSTRACT OF THE THESIS

Real-time Assessment of Fine and Ultrafine Particle (UFP) Mitigation Performance with an Air Purifier at a Local Electronic Cigarette Store

by

Che-Hsuan Lin

Master of Science in Environmental Health Sciences
University of California, Los Angeles, 2018
Professor Yifang Zhu, Chair

Vape shop employees and electronic cigarette users expose themselves to fine particles ($PM_{2.5}$, aerodynamic diameter <2.5 μm) and ultrafine particle (aerodynamic diameter <100 nm), which can impose risks on their health. This study evaluated the efficiency of an air purifier as a potential mitigation strategy to reduce exposure with a total of 8 real-time sampling sessions. The study found positive results on the association between the application of the air purifier and particle number concentration reduction regardless of puff frequency, whereas $PM_{2.5}$ mass concentration reduced significantly at only high puff frequency. Additional spatial analysis is recommended to optimize placement of air purifiers. In short, scientific inquiry into the efficacy of air purifiers in vape shops could help provide the background to regulate indoor air quality in vape shops, if determined necessary for protecting public health and workers' health.

The thesis of Che-Hsuan Lin is approved.

Michael Leo B. Jerrett

Shane S. Que Hee

Yifang Zhu, Committee Chair

University of California, Los Angeles

2018

I dedicate this thesis to my family:

my mother Doris, my father Thomas, and my brother Jeff,

for their unconditional love and endless support

throughout my ten-year journey in the United States.

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Acknowledgements

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1. Introduction

The use of electronic cigarettes (hereafter abbreviated as EC) has become a trend in the United States since 2006 when EC were introduced to the market. Such use encourage the business boom of vape shops for people to conduct vaping activities (e.g. sample e-liquid and purchase EC) as their social fad (CASAA, 2018). Therefore, due to the increasing popularity of EC use with more than 460 brands in the global market, it is important to understand the potential health impacts to vape shop employees and EC users, as well as potential mitigation strategies that can be applied at shops to reduce workers and EC users' exposure by improving the indoor air quality (IAQ) (Zhu et al., 2014).

An electronic cigarette is a nicotine delivery device that utilizes a battery-powered heating component to intermittently heat or aerosolize e-liquid (i.e. a mixture of chemicals with or without nicotine), where an inhalation (i.e. puff) can trigger the heating process (Zhu et al., 2014). Recent studies have found substantial amounts of fine particles ($PM_{2.5}$, aerodynamic diameter <2.5 μm), VOCs (volatile organic compounds), nicotine, and ultrafine particle (UFP, aerodynamic diameter <100 nm) in EC emissions (Schober et al, 2014; Czogala et al, 2014; Fromme et al, 2015; Zhao et al, 2016). Specifically, the main source of secondhand vaping from EC users' exhalation is the major concern about EC use in the indoor environment because previous studies have demonstrated impacts of EC on IAQ (Schober et al, 2014; Soule et al, 2016). Once the secondhand vaping is exhaled, it is subject to the air conditions in the indoor environment, which can further change its particle number concentration (PNC) and size distribution. Studies have shown that EC contains significant amounts of $PM_{2.5}$ (Geiss et al, 2015; Ingebrethsen et al, 2012; Soule et al, 2017). $PM_{2.5}$ is linked to respiratory disease, cardiopulmonary disease, myocardial infarction, airway inflammation and irritation, aggravated asthma, oxidative stress, cytotoxicity, increased emergency room and physician visits for asthma, viral infection, and decreased lung function (Schober et al, 2014; Schripp et al, 2013; Ji et al, 2016; Vardavas et al, 2012; Chan et al, 2017; Pope, 1999; Pope et al, 1995; Wu et al, 2014). All these health impacts demonstrate the necessity of a thorough evaluation of mitigation strategies to minimize exposures from EC vaping in real-world settings.

However, there is limited research on mitigation strategies that can improve IAQ under EC use at vape shops (Bhatnagar et al, 2014; Callahan-Lyon, 2014; Cressey et al, 2014; Geiss et al, 2015; Manzoli et al, 2013). It is acknowledged that there is an increasing importance of air cleaning technologies, particularly for buildings that are designed to conserve energy by reducing ventilation rates (Zhang et al., 2011). From a survey of all American households, 30% of the survey participants owns at least one type of air cleaning devices (Shaughnessy and Sextro, 2006). Among all available air cleaning strategies, the most common ones to improve IAQ are 1. Source removal or emission control; 2. Ventilation; and 3. Air cleaning devices (US EPA et al., 2009). For the first strategy, the challenge is the identification of the pollutant sources that need to be removed or reduced (Muller, 2002). For the second and third strategies, both are common techniques for indoor spaces (Siegel, 2015). Ventilation, under low concentration of ambient pollutants, can effectively remove and dilute indoor airborne pollutants; yet, it can also become the source of pollutants and allergens (US EPA et al., 2007). Air cleaning devices, among all options, stand out as the most plausible approach to develop the mitigation strategies for vape shops.

Studies showed that air cleaners apply technologies such as HEPA (High Efficiency Particulate Air) filters to effectively remove particles without generating ozone or other harmful byproducts (Shaughnessy and Sextro, 2006; Waring et al, 2008). From the study of Xu et al. (2010), fine particle ($PM_{2.5}$, aerodynamic diameter <2.5 μm) concentrations decreased with an average of 72% with HEPA filters; meanwhile, Noh and Yook (2006) concluded that the room air cleaner was more cost-effective than the ventilation system for reducing indoor particle concentration. One of the advantages of using an air purifier is that the performance of air cleaners can be compared with Clean Air Delivery Rate (CADR), which is the metric that accounts for particle removal efficiency and flow rate (Noh and Yook, 2016; Shaughnessy et al., 1994; Offermann et al., 1985; Zhang et al., 2011). Another advantage of air cleaners is portability, so they can be placed at desired locations where air cleaning are needed (Novoselac and Siegel, 2009).

Because air purifier performance is usually examined in a controlled laboratory setting (e.g. chamber study of portable air cleaners) or in classrooms for general public activities, the results may not best reflect real-life commercial vape shops that involve EC use (Zhang et al., 2011; Waring et al., 2008). To fill the data gaps, the goal of this study is to conduct real-time evaluation on the effectiveness of air purifiers at reducing fine and ultrafine particle concentrations so that local EC vape shops can consider air purifiers as one of the air particulate mitigation strategies. Findings from the study can even support regulatory efforts with effective indoor air mitigation strategies that can reduce related exposures for employees or EC users at vape shops.

For this study, the focus was to investigate the real-time difference between the concentration exposure to $PM_{2.5}$ and UFP under the presence or absence of air purifier, while applying statistical model for efficiency evaluation of air purifier application at the local vape shops. Therefore, the hypothesis was that for both $PM_{2.5}$ mass concentration and UFP count concentration (PNC) in the presence of air purifier, regardless of puff frequencies, are lower than those under the absence of air purifier. This study may be the first to substantiate the potential of air purifiers being an effective mitigation strategy at vape shops.

2. Method and Materials

2.1 Sampling Design

A survey was conducted in February 2017 to use observative occupancy status (popular hours vs. other days of the week) as a variable to evaluate air purifier performance between two different vape shops. Issues such as limited data and lack of control resulted in an inconclusive effect of the air purifier. Instruments and the purifier malfunctioned several times, making the actual amount of data collected fewer than the planned total 8 hours. Also, particle number concentration (PNC), temperature, humidity, CO_2, and CO levels were excluded from further statistical analysis. Even though Zhao et al. (2017) characterized secondhand vaping under uniform puffing schedule in a controlled indoor setting, vaping is challenging to control at the shop. The inconclusive result from the survey might stem from its sampling design: only two hours for two sampling sessions were with-purifier status, which was conducted right after the collection of the other two-hour sessions of without-purifier sampling. Thus, when more puffing activities happened after the air purifier was turned on, the result of with-purifier data analysis could have been skewed.

The study is designed to have long sampling time to increase statistical power and use the puff frequency status as the differentiating variable instead of occupancy status. To ensure the air purifier status being independent from puffing activity, samplings were conducted on parallel days of the week with or without purifier's presence during February 2018. Eight sessions were conducted with the following conditions: two sessions with air purifier under high puff frequency (hereafter referred as HwA) compared to two sessions without air purifier under the same puff frequency (hereafter referred as HnA), and two sessions with air purifier under low puff frequency (hereafter referred as LwA) compared to two others without air purifier under the same puff frequency (hereafter referred as LnA). Each sampling session lasted approximately 8 to 9 hours, from noon to night.

The presence of air purifier was blinded to customers to prevent increased vaping activities because they knew the air purifier was in operation. In addition, the observational real-time measurement was conducted under a relatively controlled environment under shop owner's consent and willingness to cooperate; therefore, throughout the sampling sessions, we were able to have an environment that had no tobacco smoking and no cooking activities. Field logs were kept to record observations such as number of puffs with their timestamps (puff frequency), occupancy, puffing directions, and all other observed activities. For occupancy and puff frequency, five minutes was the observed average duration customers typically stay to sample the e-liquid through vaping at the shop.

2.2 Study Site

EC stores, also called vape shops, generally open seven days a week from 11am to midnight with the most popular hours from Thursdays to Saturdays. This study only sampled at one vape shop to restrict the variables such as shop sizes, shop types, and available ventilation systems. The shop is located in a plaza. The shop size, 168 m^3, is within the parameters of the air purifier's optimal range, which is 349 ft^2 (= 185 m^3) or smaller. During sampling sessions, the windows were always closed, while the inside doors were open to direct access to the restroom. For the main entrance to the shop, the door was closed at all times except for the brief time when customers entered or left the shop. Since there is no presence of forced ventilation nor natural ventilation, the air exchange rate of the shop is 0.2 h^{-1}. The sitting area right next to the main vaping area is the location where customers sample the e-liquid and conduct constant vaping activities, while the main social area is where customers occasionally perform vaping activities between conversations. The exact spatial illustration of sampling site floor plan is shown in Figure 1.

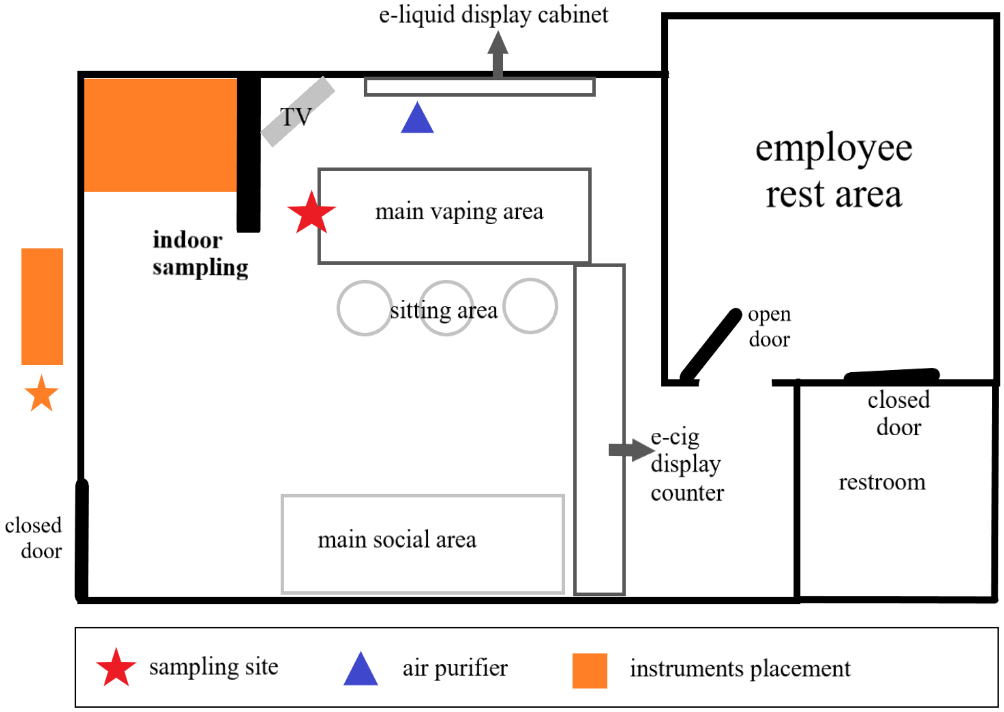


Figure 1. Spatial illustration of instrument placement and sampling site. The sampling site is located near the main vaping area, while the air purifier is placed between the e-liquid display cabinet and the main vaping area to best avoid EC users from directly seeing the presence of air purifier.

2.3 Instruments and Analysis Tools

At the shop, the level of $PM_{2.5}$ and UFP were sampled simultaneously with real-time sampling instruments. The instrument placement in the shop is spatially illustrated in Figure 1. All real-time instruments were synchronized beforehand to a satellite-signaled clock and were calibrated before data collection.

For the Condensation Particle Counter (CPC 3007, TSI Inc., St. Paul, MN), flow rates were measured and a zero-response check was conducted with a HEPA filter on the inlet before and after each sampling. $PM_{2.5}$ mass concentration was recorded with DustTrak (DustTrak II Aerosol Monitor 8532, TSI Inc., St. Paul, MN) at 1-second intervals, whereas PNC was monitored with CPC at 1-second intervals. Additional measurements such as carbon dioxide (CO_2), carbon monoxide (CO), temperature, and relative humidity were collected by Q-Trak Indoor Air Quality monitor (Model 8550, TSI Inc., St. Paul, MN) at 1-minute intervals. The data output of DustTrak was calibrated with a gravimetric calibration curve to refine the measured $PM_{2.5}$ values according to spectrometry-based readings in a chamber setting, which best reflect the actual $PM_{2.5}$ mass concentration (Zhao et al., 2017; Figure 1A). Two sets of aforementioned instruments were placed indoor and outdoor, respectively, for $PM_{2.5}$ and UFP outdoor baseline. The selected air purifier is the Holmes True HEPA Air Purifier (Model HAP 8650, Sunbeam Products Inc., Boca Raton, FL) that uses a carbon odor filter to trap and remove particles size down to 0.3µm with 99.7% efficiency (Baechler, 1991). The mechanism of HEPA filters is to force air with a fan through filter media (Waring et al, 2008). The mode was set at its highest air purifier setting during the sampling and the filter was cleaned according to the instruction in the manual before each session.

All data analyses were conducted with Microsoft® Excel® and R© Studios. All measured data were averaged to 5-minute data points for better statistical power. The data was analyzed according to the puff frequency status because from a previous study, the PNC and count median diameter of the EC aerosol increases with a longer puff duration and higher puff flow rate (Zhao et al, 2016). Additionally, the puff frequency shows greater correlation to both $PM_{2.5}$ concentration and PNC (with R^2 of 0.55 and 0.54, respectively) than the occupancy status (R^2 of 0.30 and 0.25) (Figure 2A and 3A). The high puff frequency is defined as more than 5 puffs every 5-minute average, whereas the low puff frequency is defined as less than or equal to 5 puffs per 5-minute average. Fisher's Exact Test for count data was used to examine the comparability of puff frequency between sessions with or without air purifier, while two-sample Student t-tests were conducted to assess the significance between concentrations of each session (Fisher, 1970; Mangiafico, 2015). Lastly, multiple linear regression analysis (MLR) was performed to test the significance of variables under the conditions of controlled variables. All figures were graphed by SigmaPlot 12.5 (Systat Software Inc., San Jose, CA).

3. Results

3.1 Comparability between Sessions and Summary Statistics

Before further analysis, a time series of sampling sessions without air purifier and with air purifier along with their puff frequencies is plotted to show the comparability between sessions. Figure 2 below is the time series plot of high puff frequency. The compared result of puff frequencies in session HwA and session HnA, has a p-value of 0.88 under Fisher's Exact Test for count data. The other time series plot with the same observations for low puff frequency is illustrated in Figure 4A, which the p-value is 0.68 for LwA and LnA under Fisher's Exact Test for count data. With both p-values showing insignificance, it revealed that comparing between the two high puff frequency sessions with and without air purifier is indeed comparable due to the similar pattern and peaks of puff frequency.

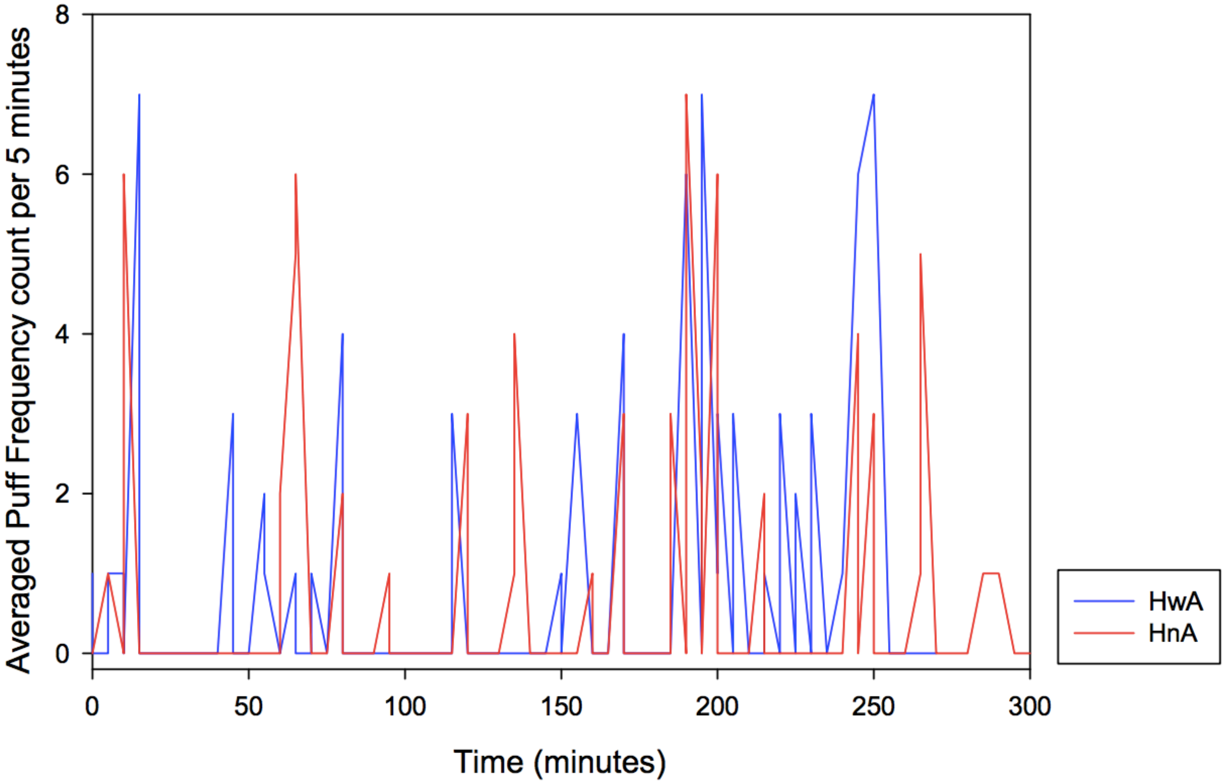


Figure 2. Average Puff Frequency Count vs. Time series for High Puff Frequency Sessions. The blue trend is for the high puff frequency with air purifier sessions, while the red-line trend is for the sessions that are high puff frequency without air pufier. The puff frequency counts are averaged of five-minute interval.

Since the data between sessions is confirmed to be comparable, further examination of the data was performed. The summary statistics of variables for $PM_{2.5}$ mass concentration and PNC of UFP count concentration by air purifier status and puff frequency status are shown with their respective mean, geometric mean, standard deviation, minimum, median, and maximum in Table 1. HnA has the highest mean and geometric mean for both $PM_{2.5}$ mass concentration and PNC. LwA has the lowest mean for $PM_{2.5}$ mass concentration, yet LnA has the lowest geometric mean for $PM_{2.5}$ mass concentration. Also, LwA has the lowest mean and geometric mean for PNC.

Table 1. Summary Statistics of $PM_{2.5}$ and UFP for all sessions

Session		HwA	LwA	HnA	LnA
$PM_{2.5}$ mass concentration (µg/m^3)	Mean	75	31	484	170
	Geometric Mean	16	11	157	10
	Standard Deviation	164	43	617	338
	Minimum	0	0	0	0
	Median	10	11	157	10
	Maximum	858	194	2,881	1942
Particle Number Concentration (#/cm^3)	Mean	11,350	10,251	24,612	11,743
	Geometric Mean	10,088	9,746	16,942	11,012
	Standard Deviation	6,003	3,206	21,021	4,508
	Minimum	4,150	4,704	3,868	6,366
	Median	9,955	10,104	16,259	10,152
	Maximum	31,550	20,152	90,860	25,943

3.2 $PM_{2.5}$ mass concentration and PNC Comparison

$PM_{2.5}$ mass concentration levels and their respective puff frequency status between sessions with and without air purifier are shown in Figure 3. Both high and low puff frequency sessions with air purifier show an overall lower concentrations spread than those without air purifier. Additionally, the session HnA has the widest range (0 to 2,881 µg/m^3) compare to others, whereas the session LwA has the smallest range (0 to 194 µg/m^3). With the result of t-test, HwA is significantly lower than HnA (p-value = 5.23 x

10^{-11}, with 95% confidence level). Meanwhile, even though LwA and LnA have approximately the same median (LwA median = 11 μg/m^3; LnA median = 10 μg/m^3), the LwA range is smaller than that for LnA's (0 to 1,942 μg/m^3). From the Student's t-test, LwA and LnA are significantly different with a p-value of 2.93 x 10^{-7} (confidence level = 95%). However, the significant difference between LwA and LnA should be further investigated via Multiple Linear Regression (MLR) statistical test, which has more factors controlled.

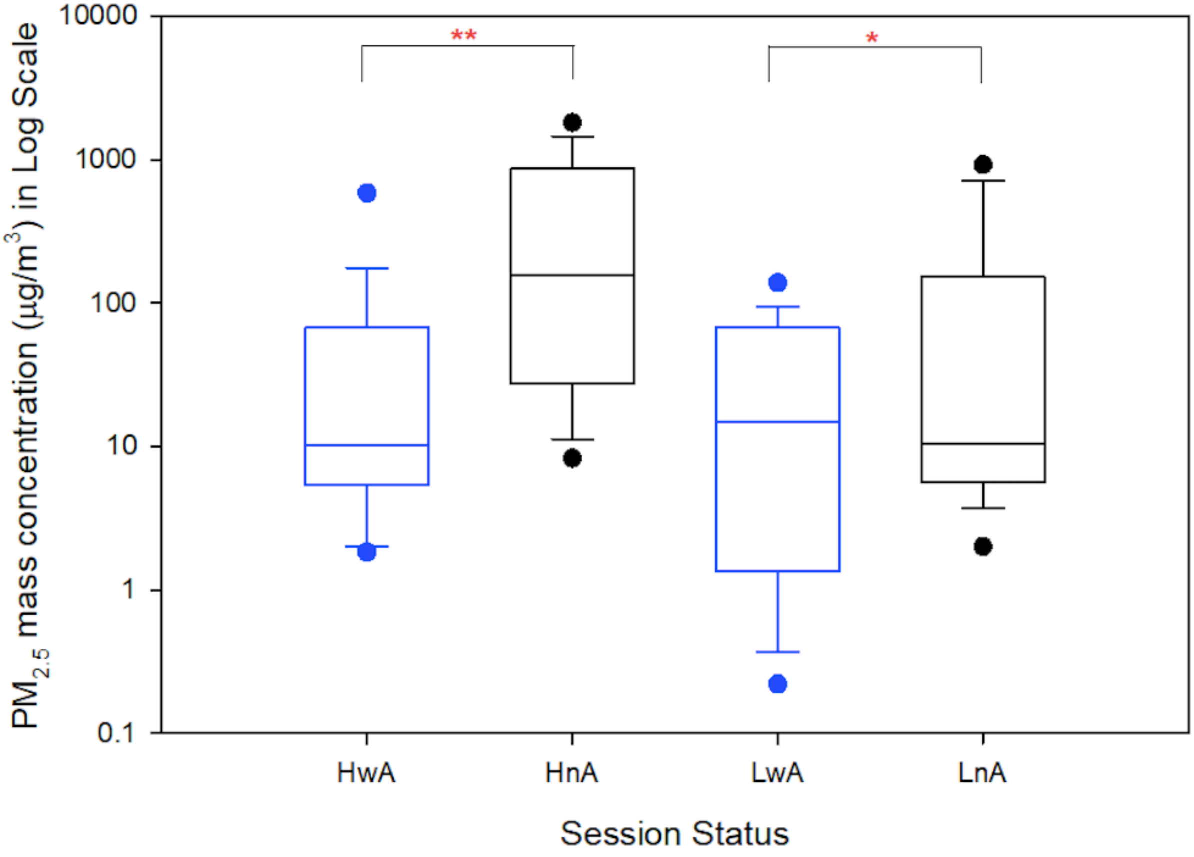


Figure 3. PM$_{2.5}$ mass concentration in Log Scale vs. Puff Frequency status and Air Purifier modes. Sessions with air purifier were colored blue, while sessions without air purifiers were colored black. Outliers within 95th percentile are shown. *significant result by Student t-test with p-value of 2.93 x 10^{-7} ; **significant result by Student t-test with p-value of 5.23 x 10^{-11}.

On the other hand, PNC for four sessions are shown in Figure 4. Except HnA, the other three groups have similar range and median (Table 1). If only comparing the high puff frequency groups, HwA is significantly lower than HnA with t-test (p-value = 2.09×10^{-12} with 95% confidence level). If only comparing the low puff frequency groups, LwA has a slightly lower median (LwA median = 10,104 #/cm^3; LnA median = 10,152 #/cm^3). Also, LwA is slightly significantly lower than LnA with its lower range values and a p-value of 0.045 (95% confidence interval) according to the t-test result. Thus, further MLR test is needed to verify its significance when all other factors are included.

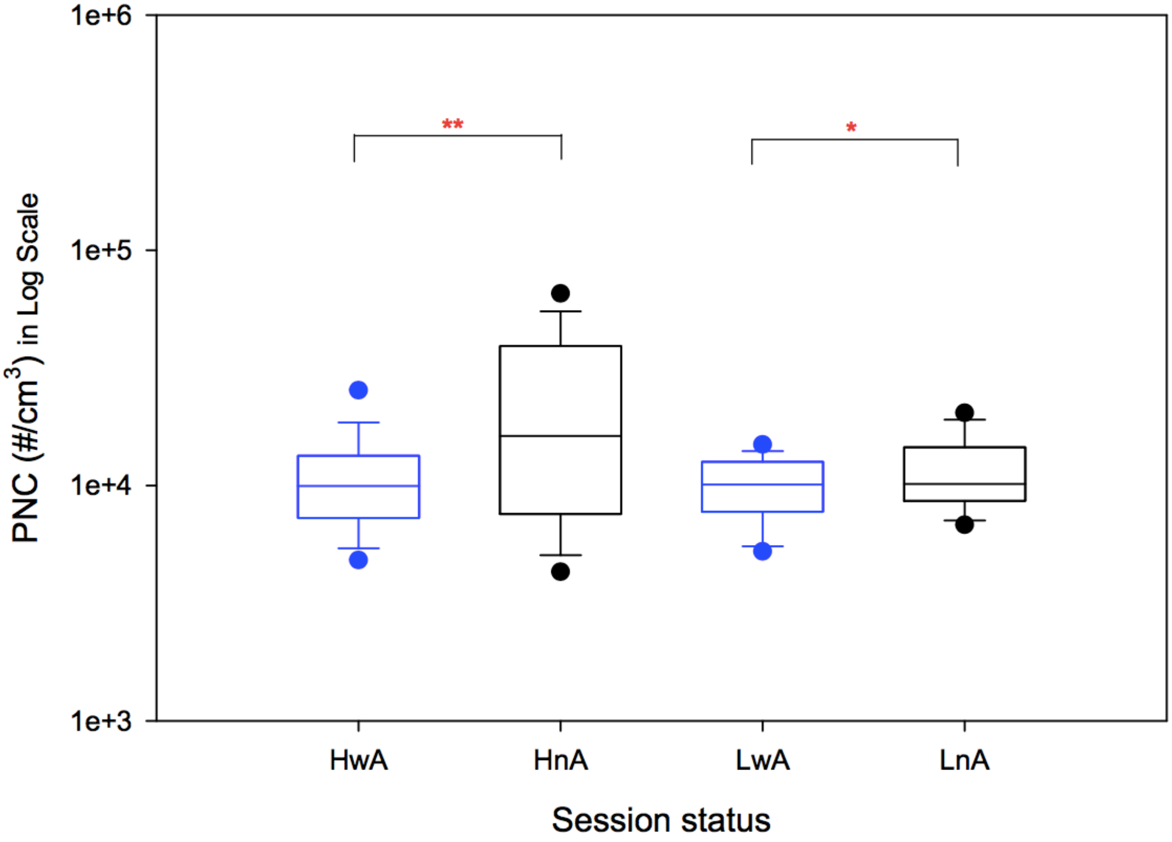


Figure 4. Particle Number Concentration (PNC) in Log Scale vs. Puff Frequency status and Air Purifier modes. Sessions with air purifier were colored blue, while sessions without air purifiers were colored black. Outliers within 95th percentile are shown. *significant result by Student t-test with p-value of 0.045 ; **significant result by Student t-test with p-value of 2.09×10^{-12}.

3.3 Multi-Linear Regression (MLR) statistical model

To determine the significance of independent variables on $PM_{2.5}$ and UFP level incorporating all sampling sessions, this study ran a Multiple Linear Regression (MLR) model with the following factors: independent factors such as $PM_{2.5}$ mass concentration and PNC, and dependent factors such as air purifier status, puff frequency status, CO_2, CO, temperature, and relative humidity. Only air purifier status (0 = off, 1 = on) and puff frequency status (0 = low, 1 = high) are dichotomous variables, while others are numeric inputs. The output results of the MLR model are shown in Table 2 with information that reflects the results such as standard error, p-value, and multiple R^2 values. Exact MLR outputs from R© studios can be found in Appendix Figure A5 to A10.

Table 2. Multiple Linear Regression model output results for Air Purifier Variable

	Session	All†	High Puff Frequency	Low Puff Frequency
$PM_{2.5}$ mass concentration ($\mu g/m^3$)	Standard Error	0.20	0.29	0.37
	p-value	0.26	0.021*	0.19
	R-squared	0.59	0.77	0.69
Particle Number Concentration ($\#/cm^3$)	Standard Error	10,172	14,739	9,434
	p-value	0.032*	0.002*	0.003*
	R-squared	0.94	0.96	0.99

† Model considers puff frequency as a dichotomous dependent variable
* Significant results under 95% confidence level

When controlling for all other factors, the effect of air purifier on PNC is significant with a p-value of 0.032 ($\alpha = 0.05$; 95% confidence level; $R^2 = 0.94$), whereas the effect of air purifier on $PM_{2.5}$ mass concentration is not significant (p-value = 0.26; $\alpha = 0.05$; 95% confidence level; $R^2 = 0.59$). However, if analyzed more specifically, under high puff frequency sessions, when controlling for all other factors, the effect of purifier status on $PM_{2.5}$ mass concentration is significant with a p-value of 0.021 ($\alpha = 0.05$, 95% confidence level; $R^2 = 0.77$). Under such conditions, temperature also has a significant effect on $PM_{2.5}$ mass concentration with a p-value of 0.005 ($\alpha = 0.05$; 95% confidence interval). In contrast, for low puff frequency sessions, when controlling for all other factors, the effect of purifier status on $PM_{2.5}$ mass concentration is also not significant (p-value = 0.19, $\alpha = 0.05$; 95% confidence interval; $R^2 = 0.69$). As for PNC, under both high and low puff frequency sessions when all other factors are accounted for, the effect of air purifier status are significant for both sessions with p-values of 0.002 and 0.003, respectively ($\alpha = 0.05$; 95% confidence interval). The corresponding R^2 values are 0.96 and 0.99.

4. Discussion

The study found positive results on the association between the application of air purifier and PNC reduction regardless of puff frequency, and $PM_{2.5}$ mass concentration reduction under high puff frequency.

In general, sessions with the air purifier have lower $PM_{2.5}$ and UFP concentration levels than respective sessions without air purifier, regardless of puff frequencies. HnA (i.e. high puff frequency with no air purifier) has the highest overall levels for both $PM_{2.5}$ and UFP. However, according to the MLR model, the regression results indicate that PNC has significant decreases in the presence of air purifier regardless of puff frequency status. On the other hand, $PM_{2.5}$ mass concentration only has significant reduction with the presence of air purifier under high puff frequency sessions, while such reduction is not significant under low puff frequency sessions. Therefore, air purifier has a significant impact on $PM_{2.5}$ mass concentration at shops in real-time settings, while it does not have significance under a controlled setting that MLR model reflects. The insignificance might be attributed to the fact that the median $PM_{2.5}$ mass concentration for LnA sessions are already low (range = 0 to 1,942 $\mu g/m^3$, median = 10 $\mu g/m^3$), so the marginal difference compared to LwA sessions' median (range = 0 to 194 $\mu g/m^3$, median = 11 $\mu g/m^3$) resulted in a statistical insignificance. However, the range of LwA session is almost a factor of 10 lower than that of LnA sessions, implying that LnA sessions still could have generally higher concentration levels for both $PM_{2.5}$ and UFP in real settings.

Additionally, there are two interesting findings from the results: 1. From the boxplot, the prediction is that LwA vs. LnA difference for $PM_{2.5}$ mass concentration is significant, whereas that for PNC might not be significant; however, the MLR with all other factors controlled revealed the opposite of the prediction. Thus, there are other variables in the environment that might influence such results, especially with the MLR model for $PM_{2.5}$ mass concentration showing a relatively low R^2 value, indicating the potential of further added variables; 2. Other than "air purifier" as the variable that shows significance, the variable "temperature" in the MLR model also exhibits significance, except for $PM_{2.5}$ mass concentration at low puff frequency sessions. Nonetheless, temperature may have play a role in affecting the concentration of $PM_{2.5}$ and UFP or data collection environment. Also, for PNC under high puff frequency, the variable "relative humidity" is also significant; however, the p-value 0.045 is close to 0.05, which such significance can be improved if the sample size or power of our study is increased.

The limitations of this study include the inability to generalize, equipment and air purifier placement in the shop, and data analysis decisions on vaping activities. Since this study focuses on only one shop to avoid uncontrolled lurking variables, the challenge is to generalize this study's results to all vape shops. Temperature's impact on $PM_{2.5}$ and UFP levels suggests additional samplings at more vape shops. The location of the equipment and their spatial relationship with the air purifier may also influence the results. A study showed that the overall particle removal change can be a factor of 2.5 difference with effective positioning of portable cleaning device and the occupants' exposure to particles can be strongly affected (Novoselac and Siegel, 2009). From the design, the data collection site is relatively close to the air purifier when given a large lounge space. Thus, if further sampling sessions can be done with various air purifier placements, the results might be more reproducible. Lastly, during data analysis, sharp peaks may not be attributed to vaping activities because of particle dispersion, average values per five or one minute interval, and the direction of the airflow in the shop due to well-mixing effect of the natural ventilation.

5. Conclusions

The hypothesis, "the difference of $PM_{2.5}$ and UFP levels between the air purifier status are significant regardless of puff frequencies," is only partially supported by this study due to the dynamic of variable influence, statistical analysis, and limitations. The study did find positive results on the association between the application of air purifier and

PNC reduction regardless of puff frequency, and $PM_{2.5}$ mass concentration reduction under high puff frequency. Hence, more samplings at additional shops for similar study design should be conducted to increase the generalizability of the study, yet remain the comparability of environment and data quality. The results also showed that additional examination on spatial relationship is necessary with information such as air exchange rates, clean air delivery rate of the filter and shop, and direction of the airflow would help better determine the effectiveness of the air purifier.

Moreover, to claim air purifier as a valuable control in reducing $PM_{2.5}$ mass concentration and PNC, the study can also further compare its data with the primary National Ambient Air Quality Standard for $PM_{2.5}$ and UFP. If the results exceed the standard, it indicates that indoor particulate matter concentrations in vape shops can pose a public health issue. In short, there are currently no requirements established for businesses such as vape shops to acquire permits, install air filtration or ventilation systems. That being the case, scientific inquiry into the efficacy of air purifiers in vape shops can help provide the background to effectively regulate indoor air quality in vape shops, if determined necessary for protecting public health and workers' health.

Supplemental Information

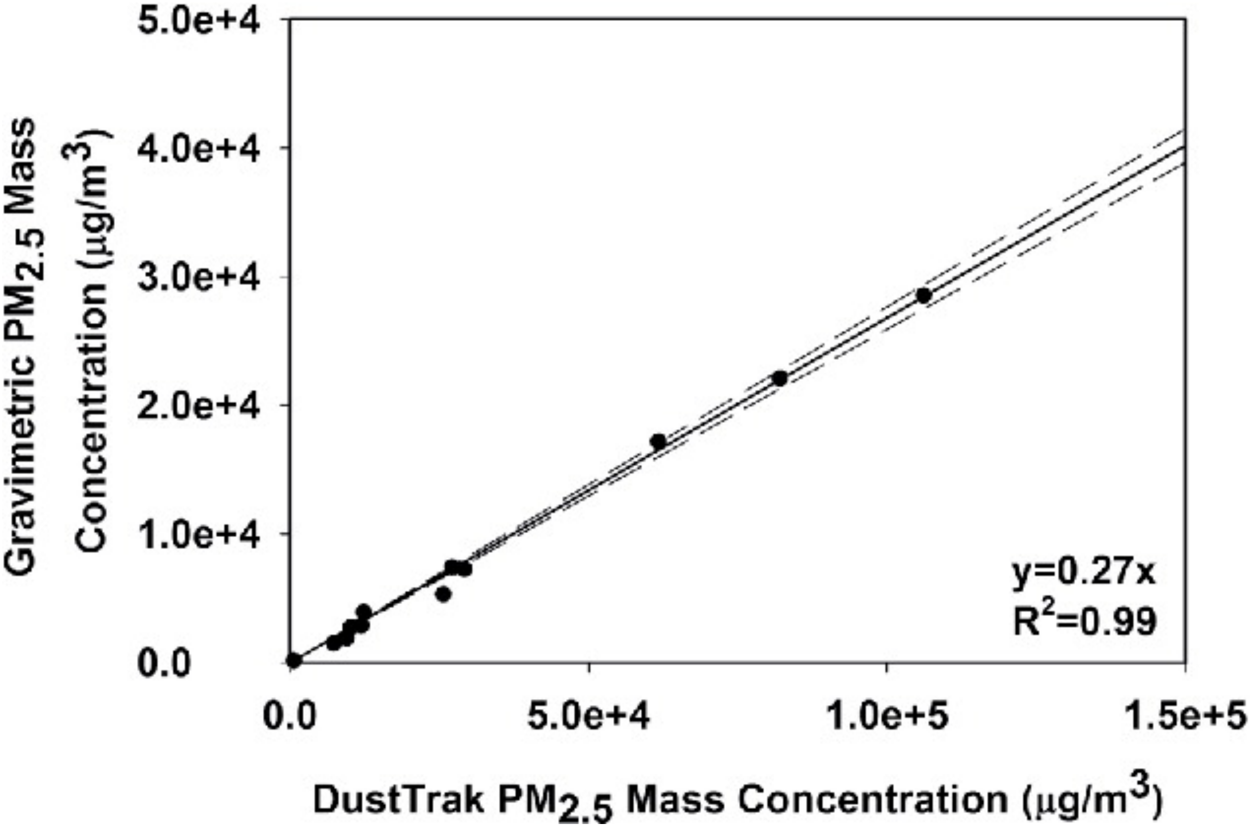


Figure 1A. $PM_{2.5}$ DustTrak Gravimetric Calibration curve. The calibration was spectrometry-based from electronic cigarette emissions. 95% confidence intervals are showed as the dashed lines.

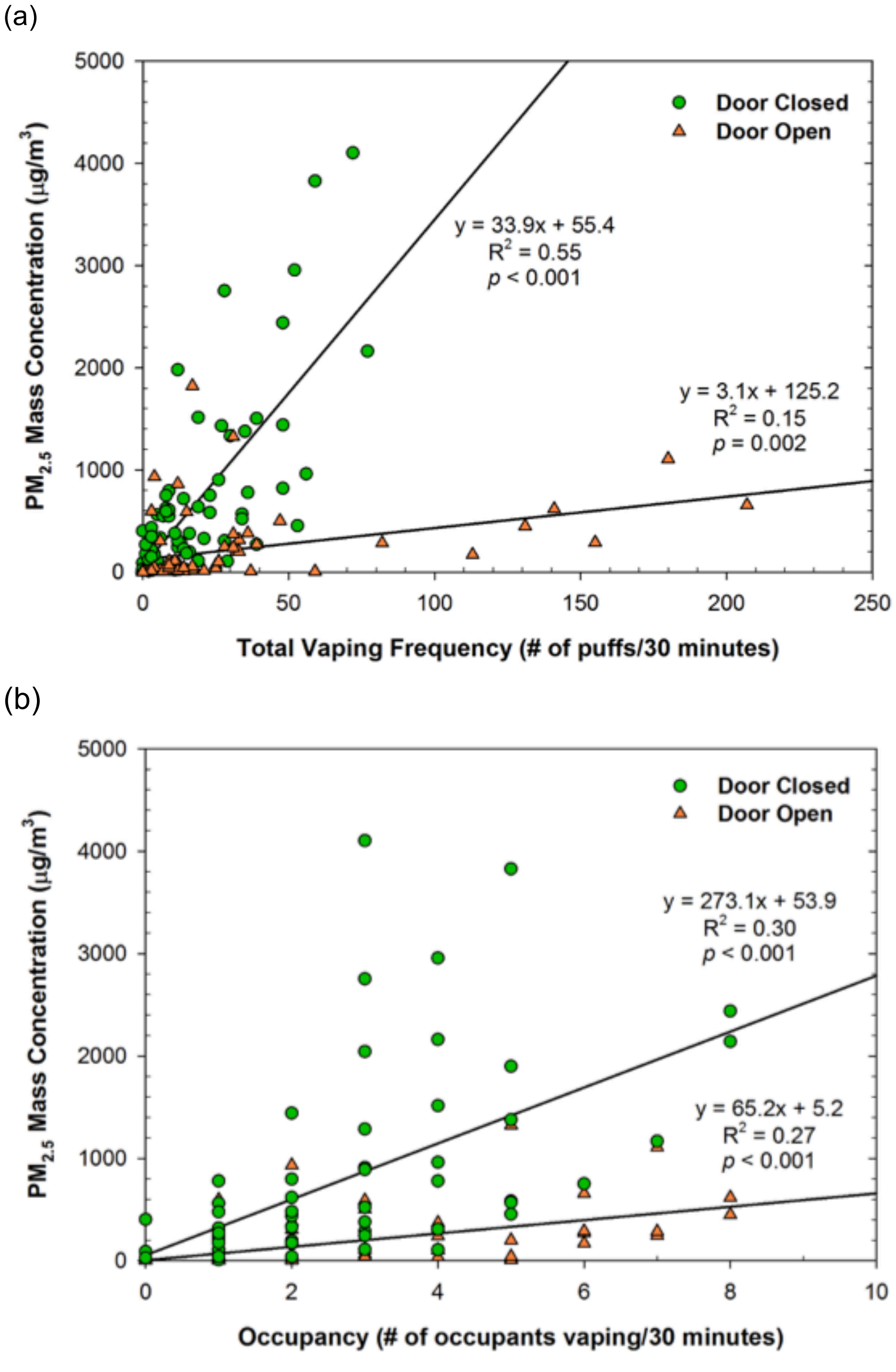


Figure 2A. Correlation of $PM_{2.5}$ mass concentration vs. Puff Frequency and Occupancy. Total Vaping Frequency (a) is shown to have higher correlation to $PM_{2.5}$ than occupancy (b) under the condition of closed doors. Total Vaping Frequency is the same as puff frequency define in this study.

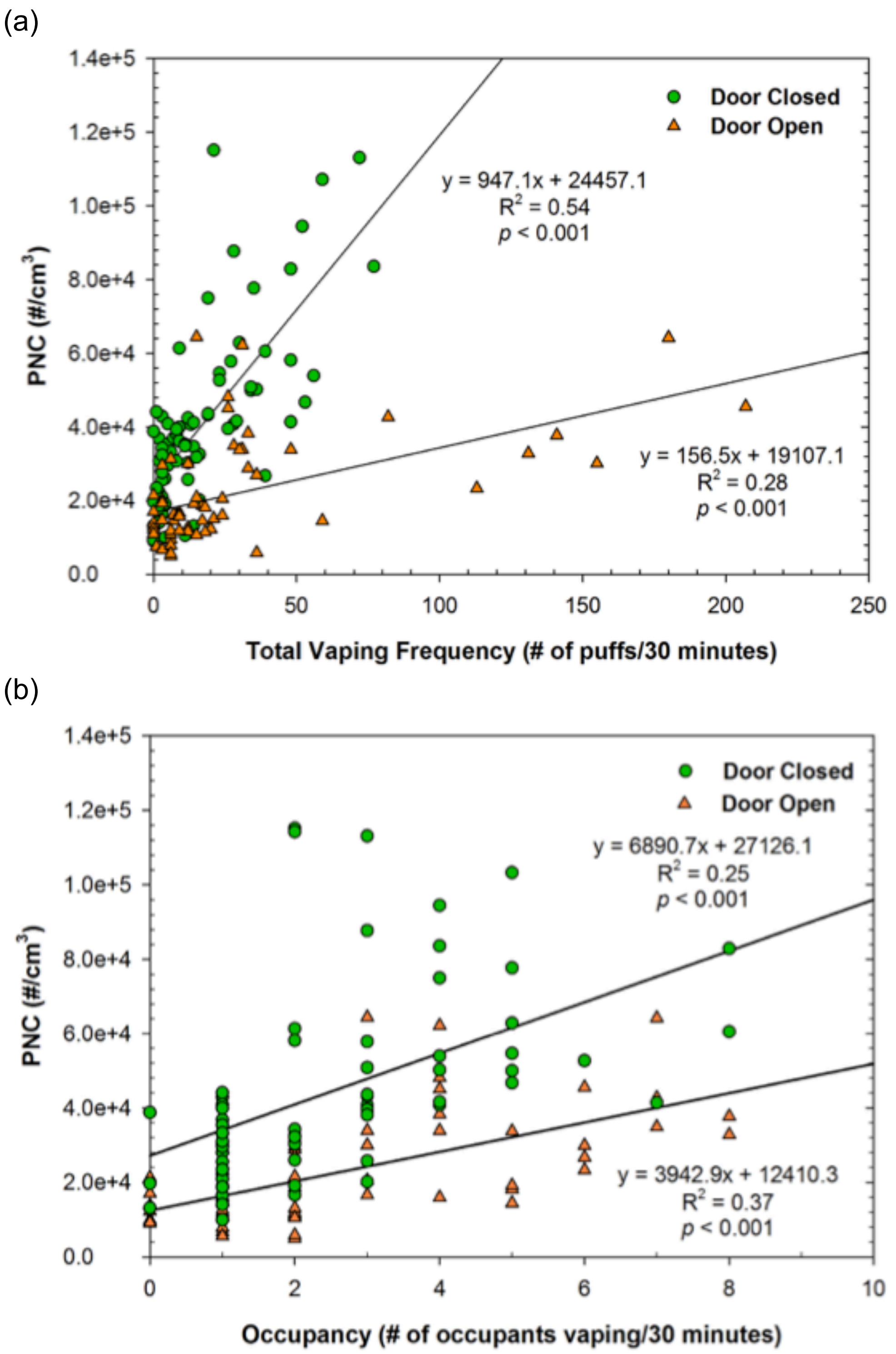


Figure 3A. Correlation of UFP count concentration (Particle Count Concentration, PNC) vs. Puff Frequency and Occupancy. Total Vaping Frequency (a) is shown to have higher correlation to $PM_{2.5}$ than occupancy (b) under the condition of closed doors. Total Vaping Frequency is the same as puff frequency define in this study.

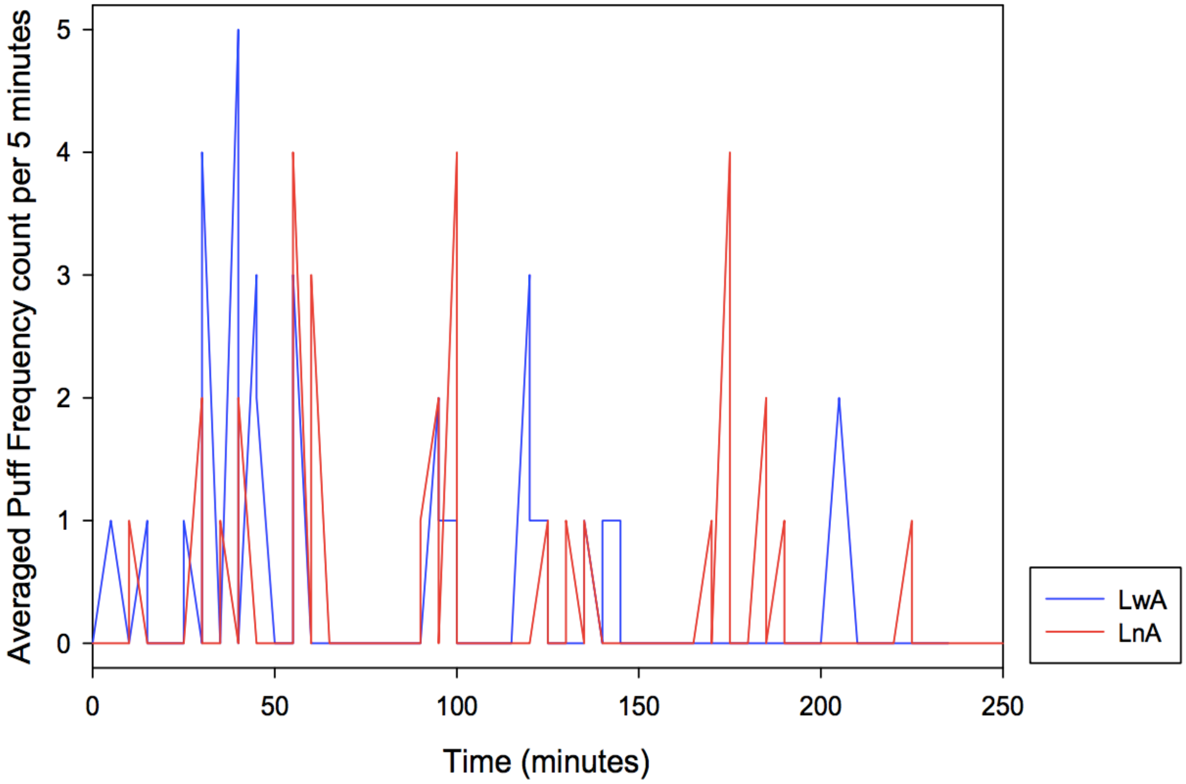
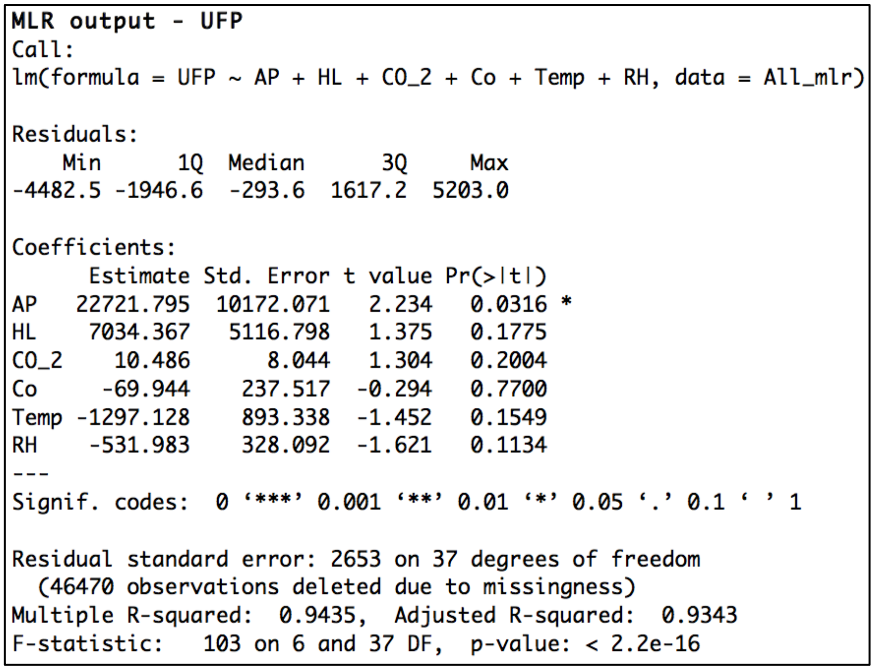


Figure 4A. Average Puff Frequency Count vs. Time series for Low Puff Frequency Sessions. The blue trend is for the low puff frequency with air purifier sessions, while the red-line trend is for the sessions that are low puff frequency without air pufier. The puff frequency counts are averaged at five-minute intervals.



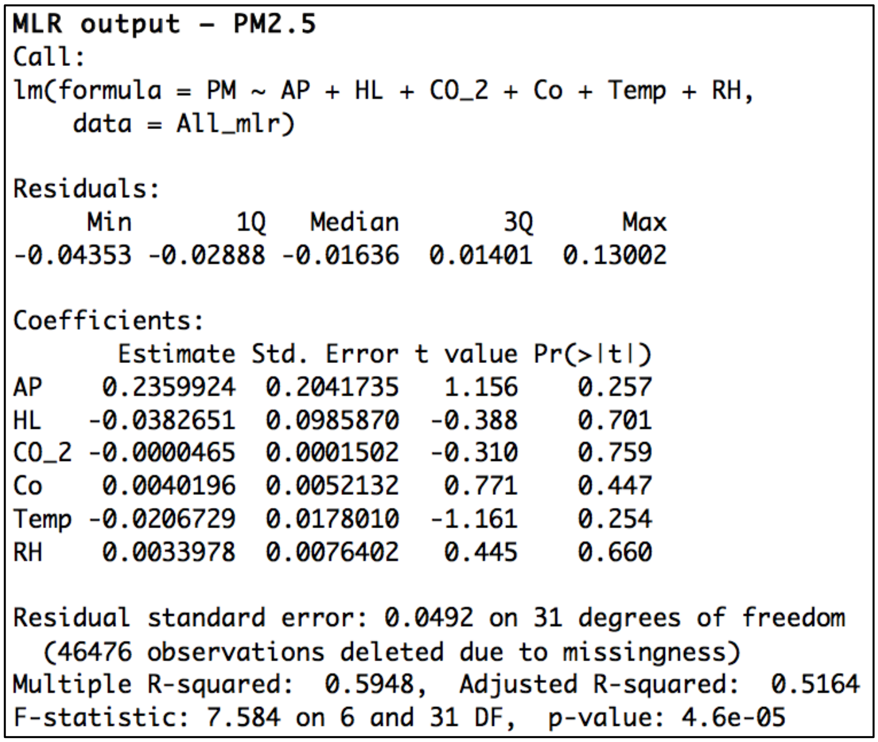
```
MLR output - UFP
Call:
lm(formula = UFP ~ AP + HL + CO_2 + Co + Temp + RH, data = All_mlr)

Residuals:
    Min      1Q  Median      3Q     Max 
-4482.5 -1946.6  -293.6  1617.2  5203.0 

Coefficients:
      Estimate Std. Error t value Pr(>|t|)  
AP   22721.795  10172.071   2.234   0.0316 *
HL    7034.367   5116.798   1.375   0.1775  
CO_2    10.486      8.044   1.304   0.2004  
Co     -69.944    237.517  -0.294   0.7700  
Temp -1297.128    893.338  -1.452   0.1549  
RH    -531.983    328.092  -1.621   0.1134  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2653 on 37 degrees of freedom
  (46470 observations deleted due to missingness)
Multiple R-squared:  0.9435,  Adjusted R-squared:  0.9343 
F-statistic:   103 on 6 and 37 DF,  p-value: < 2.2e-16
```

Figure 5A. PNC MLR output. UFP stands for the variable PNC; AP = air purifier, HL = puff frequency status, CO_2 = CO_2 (ppm), Co = CO (ppm), Temp = Temperature (°C), RH = Relative Humidity (%).



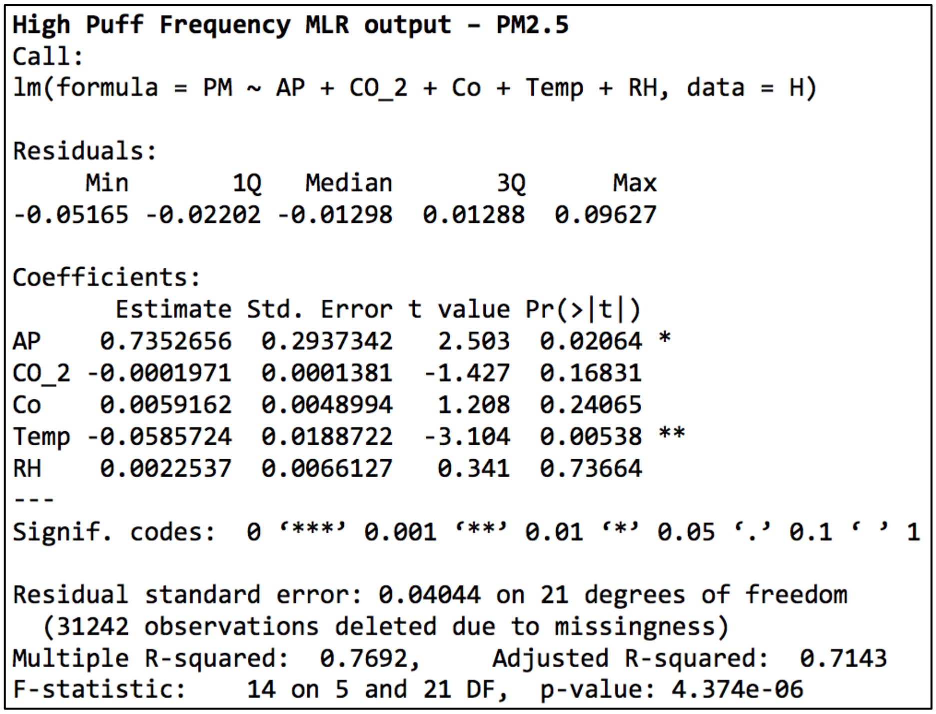
```
MLR output – PM2.5
Call:
lm(formula = PM ~ AP + HL + CO_2 + Co + Temp + RH, 
    data = All_mlr)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.04353 -0.02888 -0.01636  0.01401  0.13002 

Coefficients:
       Estimate Std. Error t value Pr(>|t|)
AP    0.2359924  0.2041735   1.156    0.257
HL   -0.0382651  0.0985870  -0.388    0.701
CO_2 -0.0000465  0.0001502  -0.310    0.759
Co    0.0040196  0.0052132   0.771    0.447
Temp -0.0206729  0.0178010  -1.161    0.254
RH    0.0033978  0.0076402   0.445    0.660

Residual standard error: 0.0492 on 31 degrees of freedom
  (46476 observations deleted due to missingness)
Multiple R-squared:  0.5948,  Adjusted R-squared:  0.5164 
F-statistic: 7.584 on 6 and 31 DF,  p-value: 4.6e-05
```

Figure 6A. $PM_{2.5}$ MLR output. PM stands for the variable $PM_{2.5}$ mass concentration; AP = air purifier, HL = puff frequency status, CO_2 = CO_2 (ppm), Co = CO (ppm), Temp = Temperature (°C), RH = Relative Humidity (%).



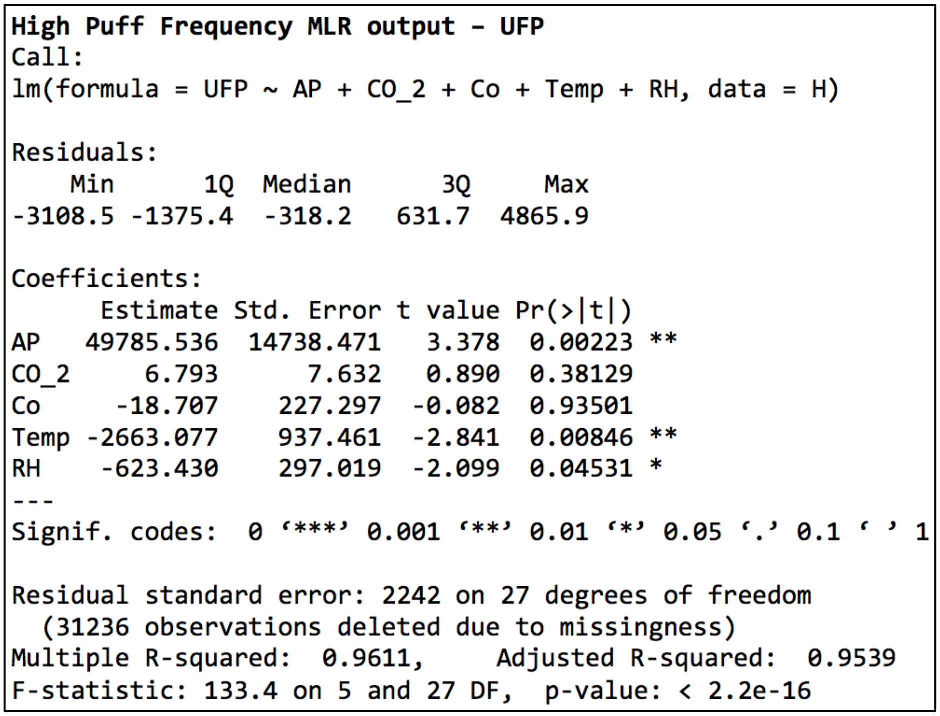
```
High Puff Frequency MLR output – PM2.5
Call:
lm(formula = PM ~ AP + CO_2 + Co + Temp + RH, data = H)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.05165 -0.02202 -0.01298  0.01288  0.09627 

Coefficients:
       Estimate Std. Error t value Pr(>|t|)   
AP    0.7352656  0.2937342   2.503  0.02064 * 
CO_2 -0.0001971  0.0001381  -1.427  0.16831   
Co    0.0059162  0.0048994   1.208  0.24065   
Temp -0.0585724  0.0188722  -3.104  0.00538 **
RH    0.0022537  0.0066127   0.341  0.73664   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.04044 on 21 degrees of freedom
  (31242 observations deleted due to missingness)
Multiple R-squared:  0.7692,	Adjusted R-squared:  0.7143 
F-statistic:    14 on 5 and 21 DF,  p-value: 4.374e-06
```

Figure 7A. High Puff Frequency PM$_{2.5}$ MLR output. PM stands for the variable PM$_{2.5}$ mass concentration; AP = air purifier, HL = puff frequency status, CO_2 = CO$_2$ (ppm), Co = CO (ppm), Temp = Temperature (°C), RH = Relative Humidity (%).



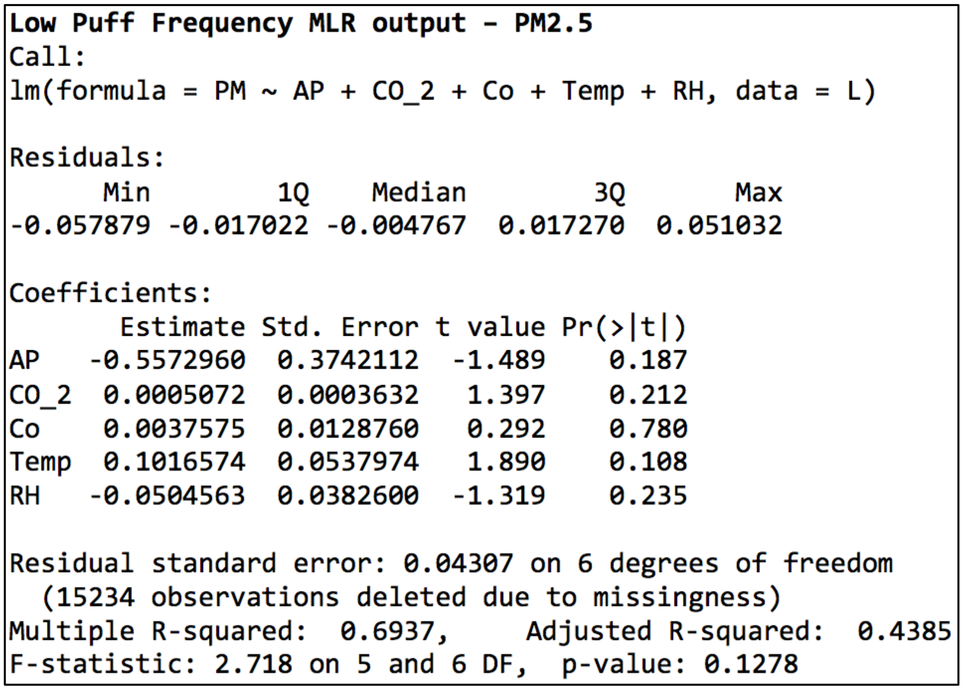
```
High Puff Frequency MLR output – UFP
Call:
lm(formula = UFP ~ AP + CO_2 + Co + Temp + RH, data = H)

Residuals:
    Min      1Q  Median      3Q     Max 
-3108.5 -1375.4  -318.2   631.7  4865.9 

Coefficients:
      Estimate Std. Error t value Pr(>|t|)   
AP   49785.536  14738.471   3.378  0.00223 **
CO_2     6.793      7.632   0.890  0.38129   
Co     -18.707    227.297  -0.082  0.93501   
Temp -2663.077    937.461  -2.841  0.00846 **
RH    -623.430    297.019  -2.099  0.04531 * 
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2242 on 27 degrees of freedom
  (31236 observations deleted due to missingness)
Multiple R-squared:  0.9611,	Adjusted R-squared:  0.9539 
F-statistic: 133.4 on 5 and 27 DF,  p-value: < 2.2e-16
```

Figure 8A. High Puff Frequency PNC MLR output. UFP stands for the variable PNC; AP = air purifier, HL = puff frequency status, CO_2 = CO$_2$ (ppm), Co = CO (ppm), Temp = Temperature (°C), RH = Relative Humidity (%).



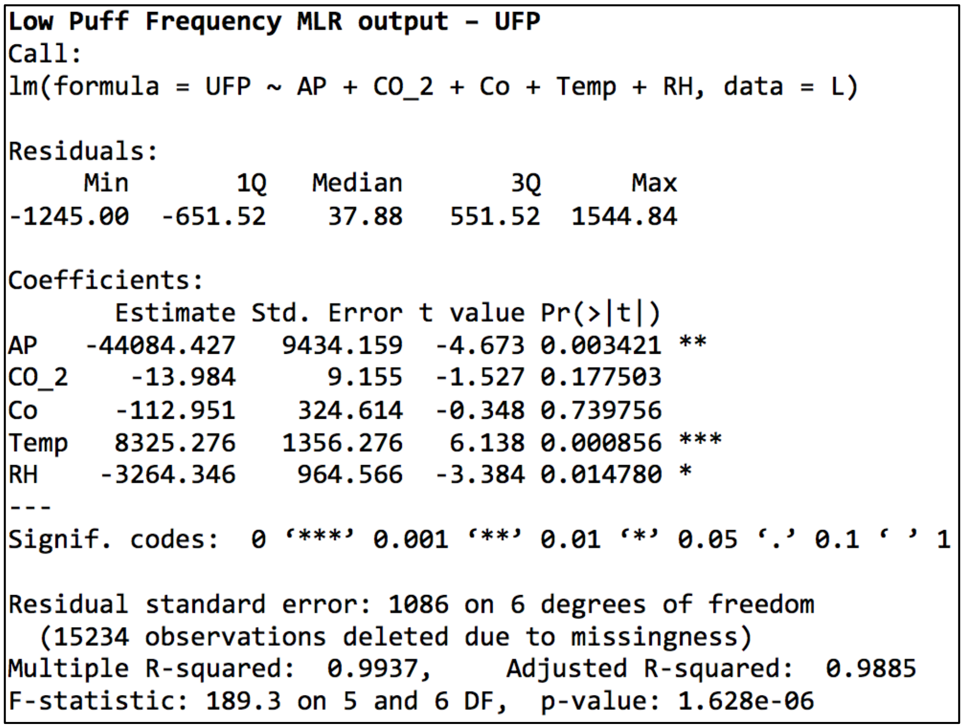
```
Low Puff Frequency MLR output - PM2.5
Call:
lm(formula = PM ~ AP + CO_2 + Co + Temp + RH, data = L)

Residuals:
      Min        1Q    Median        3Q       Max
-0.057879 -0.017022 -0.004767  0.017270  0.051032

Coefficients:
       Estimate Std. Error t value Pr(>|t|)
AP   -0.5572960  0.3742112  -1.489    0.187
CO_2  0.0005072  0.0003632   1.397    0.212
Co    0.0037575  0.0128760   0.292    0.780
Temp  0.1016574  0.0537974   1.890    0.108
RH   -0.0504563  0.0382600  -1.319    0.235

Residual standard error: 0.04307 on 6 degrees of freedom
  (15234 observations deleted due to missingness)
Multiple R-squared:  0.6937,	Adjusted R-squared:  0.4385
F-statistic: 2.718 on 5 and 6 DF,  p-value: 0.1278
```

Figure 9A. Low Puff Frequency PM2.5 MLR output. PM stands for the variable $PM_{2.5}$ mass concentration; AP = air purifier, HL = puff frequency status, CO_2 = CO_2 (ppm), Co = CO (ppm), Temp = Temperature (°C), RH = Relative Humidity (%).



```
Low Puff Frequency MLR output - UFP
Call:
lm(formula = UFP ~ AP + CO_2 + Co + Temp + RH, data = L)

Residuals:
     Min       1Q   Median       3Q      Max
-1245.00  -651.52    37.88   551.52  1544.84

Coefficients:
       Estimate Std. Error t value Pr(>|t|)
AP   -44084.427   9434.159  -4.673 0.003421 **
CO_2    -13.984      9.155  -1.527 0.177503
Co     -112.951    324.614  -0.348 0.739756
Temp   8325.276   1356.276   6.138 0.000856 ***
RH    -3264.346    964.566  -3.384 0.014780 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1086 on 6 degrees of freedom
  (15234 observations deleted due to missingness)
Multiple R-squared:  0.9937,	Adjusted R-squared:  0.9885
F-statistic: 189.3 on 5 and 6 DF,  p-value: 1.628e-06
```

Figure 10A. Low Puff Frequency PNC MLR output. UFP stands for the variable PNC; AP = air purifier, HL = puff frequency status, CO_2 = CO_2 (ppm), Co = CO (ppm), Temp = Temperature (°C), RH = Relative Humidity (%).

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