TEMPORAL VARIATIONS OF AIRBORNE ULTRAFINE PARTICLES INSIDE AND OUTSIDE OF HOMES IN AN URBAN AREA

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

In

Environmental and Water Resources Engineering

Tufts University

August 2015

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Abstract

Ultrafine particles are particles with aerodynamic diameter less than 0.1 micrometers. These particles have many origins including outdoor and indoor sources. Infiltration of outdoor particles may influence the particle number concentration (PNC) indoors; however, indoor sources such as cooking and smoking may also have a significant contribution to the particle number concentration indoors. Our study area was focused on two cities of Boston and Chelsea, MA. TSI model 3783 was employed to measure PNC for 24 homes for six weeks, switching between HEPA and sham filtration for three weeks. Our results show that median hourly indoor PNC variations for each week during HEPA have spikes higher than 100,000 (#/cm^3). These spikes are mostly during the evening; this may be due to cooking as the trend is common for many days in every week. Monthly PNC variations during sham measurements show that there are higher median concentrations during cold seasons compared to warm ones; however, various factors may have effect on these results including different home types, number of data points for each cluster of homes included in the season. There is an increase in median outdoor and indoor PNC during sham filtration for colder seasons compared to warmer seasons. Moreover, the effect of HEPA filtration was noticeable in the weekly indoor variations for HEPA compared to sham filtration. HEPA indoor variations were associated with lower baseline levels and higher spikes compared to sham indoor variations.

Acknowledgement

This thesis could not have been accomplished without the support, guidance and encouragement of many people. First and foremost being my committee members. In particular, I want to thank my thesis advisor Professor John Durant. I appreciate his valuable insight and guidance through the completion of this work. For this I am most thankful. I would like to thank Professor Woodin for his valuable input and guidance and support through this work. I truly appreciate it.

I would like to thank Professor Doug Brugge, for his leadership of the collaboration between Boston Puerto Rican Health Study (BPRHS) and CAFEH and for his guidance and insightful critiques and constant encouragement, which helped me immensely.

I also want to thank my colleague and friend, Matthew Simon. His help, encouragement and patience in teaching me the steps and processes of data collection and analysis are much appreciated.

Finally I am thankful to my parents, who provided the motivation to succeed, the capacity to achieve and supported me over great distance during these years.

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1.0: Introduction

Possible association between exposure to airborne particulate matter and adverse health effects such as respiratory and cardiovascular disease has been under investigation for many years in epidemiological and toxicological studies (Dockery & Pope 1993, 1994). Since $PM_{2.5}$ and PM_{10} (particles with an aerodynamic diameter smaller than 2.5 and 10 micrometers, respectively) were the focus of most of the studies in the past few decades, current US federal ambient air quality standards are limited to these two parameters. However, UFP (particles with an aerodynamic diameter less than 0.1 micrometer) has been the focus for recent studies because of its chemical properties. These particles can carry a considerable amount of toxic pollutants per unit mass (Sioutas et al., 2005). Peters et al. (1997) suggested that the effect of UFP on health was greater than fine particles on non-smoking asthmatic participants in a case study in Germany. The main origin of these particles is considered to be from vehicular emissions (Hasheminassab et al., 2013). Trend analysis of indoor and outdoor air with non-central site concentration measurements and source contributions were studied in a not near highway location, suggesting that indoor activity such as cooking contributed more than outdoor measurements (Abt et al., 2000). Most of the studies concluded that indoor activities such as cooking influence indoor UFP number concentrations (Wallace et al., 2011; Abt et al., 2000).

This thesis seeks to determine the temporal variation of indoor and outdoor particle number concentration within Puerto Rican communities in two different locations in the Boston metropolitan area.

Previous research suggests that UFP exposure includes indoor and outdoor sources, while the major source of UFP in indoor air was indoor activities within 19 categories which was investigated by He et al. (2004). Also, this study assigned each specific participants activity (among 19 categories) during the day to the number of particles measured with a portable condensation particle counter (CPC) (Wallace & Ott 2011; Abt et al., 2000; He et al., 2004). UFP indoor concentration was mostly from indoor-generated UFPs in the condition that ambient UFPs with minimum infiltration factors were infiltrated (Kearney et al., 2010; Long et al., 2001).

CAFEH investigated the exposure of UFP in near-highway neighbors in Somerville, MA, using a central and near-highway monitoring site, suggesting the significance of the monitoring sites in neighborhoods where local emissions of UFP is considerable (Fuller et al., 2012). This study showed that the level of indoor PNC in near-highway homes was substantially affected by outdoor PNC (particle number concentration), time of the day and meteorology. Dennekamp et al. focused on the effect of indoor activity such as cooking and frying on the number of ultrafine particles being generated by these activities. Their results suggest that cooking in a "poorly ventilated kitchen" increases the number of ultrafine particles and nitrogen oxide concentrations indoors causing adverse health effects. Indoor-outdoor ratio were compared for PM_{10} in a study for nine homes in UK suggesting that a person will inhale less than one-third of the outdoor origin pollutant by remaining indoors (Alzona et al., 1979). Monn et al. (1997) investigated the indoor/outdoor relationship in 17 naturally ventilated homes in Switzerland for PM_{10} and $PM_{2.5}$. Their results show that I/O ratio was 0.7 and that smoking indoors affected the I/O ratio the most. Morawski et al. focused on I/O ratio for 16 homes with minimum and normal ventilation conditions in suburban areas in Australia. Their results demonstrated that 0.2 I/O ratio for minimum ventilation condition could not be a good predictor for indoor particle concentrations; however, higher I/O ratios with a maximum of 2.5 may be a good estimation. This thesis will concentrate on I/O ratios for ultrafine particles in homes in the Boston metropolitan area. No study has focused on comparison between HEPA and sham filtration period indoor and outdoor weekly as an intervention trial to describe the effectiveness of HEPA filtration on air quality.

The objective of this thesis is to investigate seasonal and daily trends in PNC in homes in Boston and Chelsea, MA. Also, I investigated the monthly indoor, outdoor and indoor-outdoor ratio variations for each of the 24 participants in this study stratified by sham and HEPA. A comparison among seasonality and monthly variations during sham filtrations has been accomplished too.

2.0 Methods

This study was part of a larger study CAFEH (Community Assessment of Freeway Exposure and Health Study), which is a community-based participatory research (CBPR) project. CAFEH investigates the effect of traffic pollution and cardiovascular disease (CVD). Data collection for the collaboration with the BPRHS has been implemented by using a CPC placed in the home of the 24 participants. The data collection has been conducted for two regions, Boston and Chelsea area, each having 14 and 10 participants respectively from 3 May 2012 to 21 October 2013 for Boston and from 6 Jan 2014 to 9 Dec 2014 for Chelsea. All of the data were collected in the homes of Puerto Rican adults. The data collected included 30-second and 1-min mean PNC (particle number concentration) measurements.

2.1. Site Description

The figures below show the two different areas under study. The first one is for Boston participants in which the red dots are the participant houses.

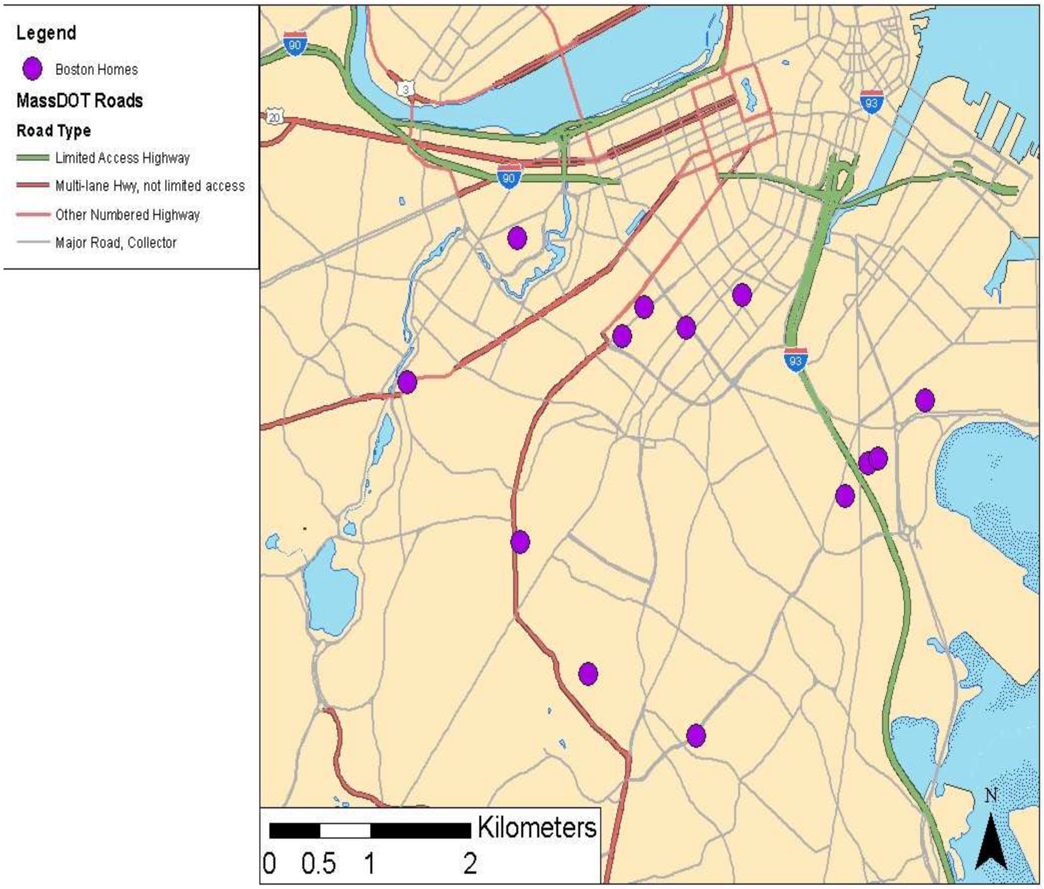


Figure 1. Boston area participant's spatial distribution of the monitoring locations (cartographer: Matthew Simon).

Figure 2 shows the details for Chelsea area PNC measurements. The green dots are showing the participant's home locations.

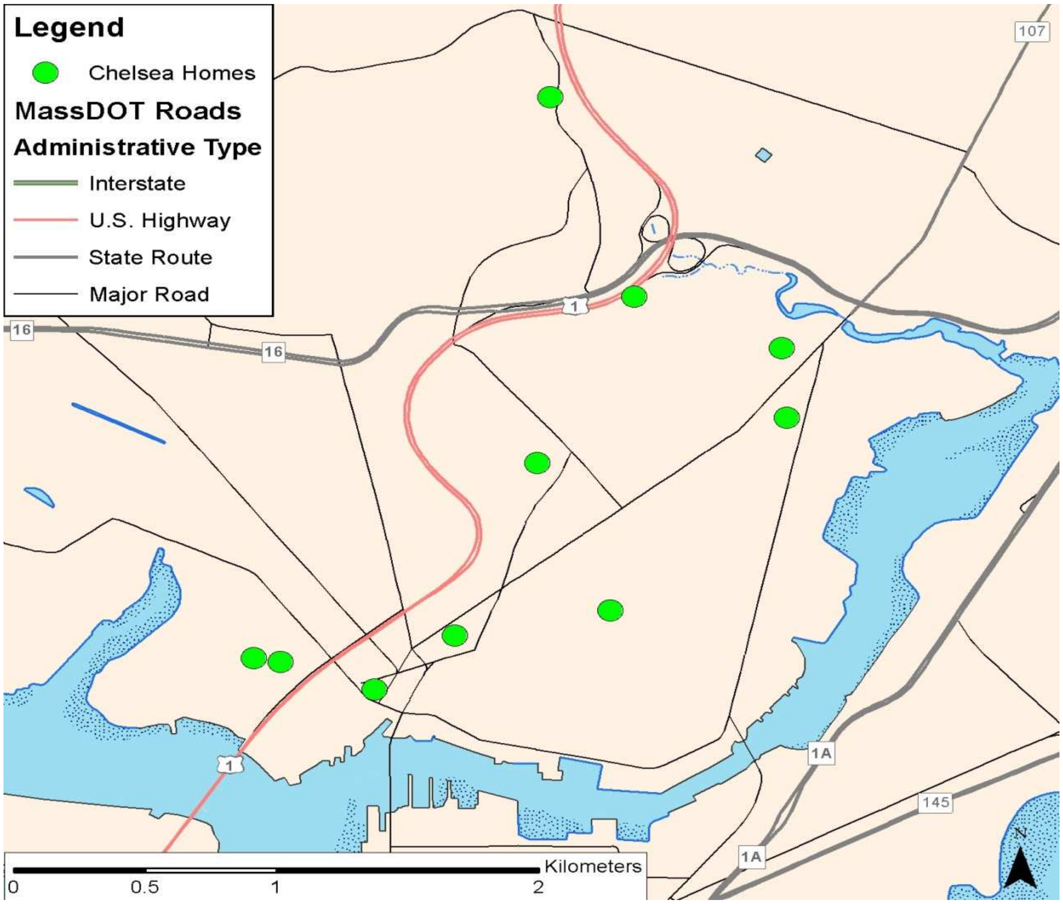


Figure 2. Chelsea area participant's spatial distribution of the monitoring participants (Cartographer: Matthew Simon).

The participants were selected from the Boston Puerto Rican Health Study cohort. There are hundreds of possible homes, so for the in-home monitoring we chose homes such that some near and some further from major roads, and also spread across the study area as evenly as possible. The data collection was conducted for a maximum of two homes concurrently in each area.

The TSI CPC data Instrument model 3783 was employed to measure particle number concentration. PNC was measured in every second and then one-minute or 30-second for each of the participants. The data for each participant switches between indoor and outdoor every 15 minutes. Therefore, we have 30 minutes of indoor data and 30 minutes of outdoor data for each hour. This instrument was chosen due to quiet operation and their short-sampling times (30s and 1min for CPC).

Table 1. Dates for each participant during HEPA and sham filtration period for Boston and Chelsea

Boston	HEPA		Sham	
Home #				
1	7-May-12	1-Jun-12	1-Jun-12	20-Jun-12
2	11-Sep-12	2-Oct-12	20-Aug-12	11-Sep-12
3	21-Jun-12	13-Jul-12	13-Jul-12	2-Aug-12
4	17-Aug-12	6-Sep-12	24-Jul-12	17-Aug-12
5	27-Sep-12	16-Oct-12	16-Oct-12	6-Nov-12
6	13-Nov-12	4-Dec-12	24-Oct-12	13-Nov-12
7	27-Feb-13	20-Mar-13	7-Feb-13	19-Feb-13
8	5-Mar-13	26-Mar-13	11-Feb-13	5-Mar-13
9	30-Apr-13	21-May-13	9-Apr-13	30-Apr-13
10	18-Apr-13	8-May-13	8-May-13	30-May-13
11	7-Jun-13	2-Jul-13	2-Jul-13	30-May-13
12	8-Jul-13	29-Jul-13	17-Jun-13	8-Jul-13
13	5-Aug-13	26-Aug-13	26-Aug-13	16-Sep-13
14	30-Sep-13	21-Oct-13	10-Sep-13	30-Sep-13

Chelsea	HEPA		Sham	
Home #				
16	21-Jan-14	13-Feb-14	13-Feb-14	6-Mar-14
17	27-Feb-14	20-Mar-14	6-Feb-14	27-Feb-14
19	24-Apr-14	15-May-14	3-Apr-14	24-Apr-14
20	30-Apr-14	21-May-14	21-May-14	11-Jun-14
21	25-Jun-14	16-Jul-14	5-Jun-14	25-Jun-14
22	31-Jul-14	21-Aug-14	10-Jul-14	31-Jul-14
23	1-Aug-14	21-Aug-14	21-Aug-14	11-Sep-14
24	11-Sep-14	2-Oct-14	2-Oct-14	23-Oct-14
25	23-Oct-14	14-Nov-14	2-Oct-14	23-Oct-14
26	28-Oct-14	18-Nov-14	18-Nov-14	9-Dec-14

2.2 Data Collection

Data was collected over six weeks (42 days) for each participant. Two different filters were examined. For the first three weeks, participants were randomly assigned to receive either the HEPA or sham filter. At the end of three weeks, filter were switched. Thus, all participants received three weeks of HEPA filtration and three weeks with the sham filter. The approximated time for indoor activities, such as cooking and cleaning, each activity was recorded. Problems with the instruments were documented. A condensation particle counter (CPC, TSI model 3783) was used to measure particles between 0.007 and 3 micrometers. The CPC inlet was connected to a solenoid that allowed the instrument to switch between measuring indoor and outdoor air (each for 15 minutes). The CPC and HEPAirX (ventilating room air purifier) were located in either the bedroom or the living room. Figure 3 illustrates the air flow through a ventilating room air purifier (HEPAirX, Air Innovations, Syracuse, NY). HEPAirX is installed in the window or wall. It has air inflow from outside and room supply outflow air from the top if the instrument.

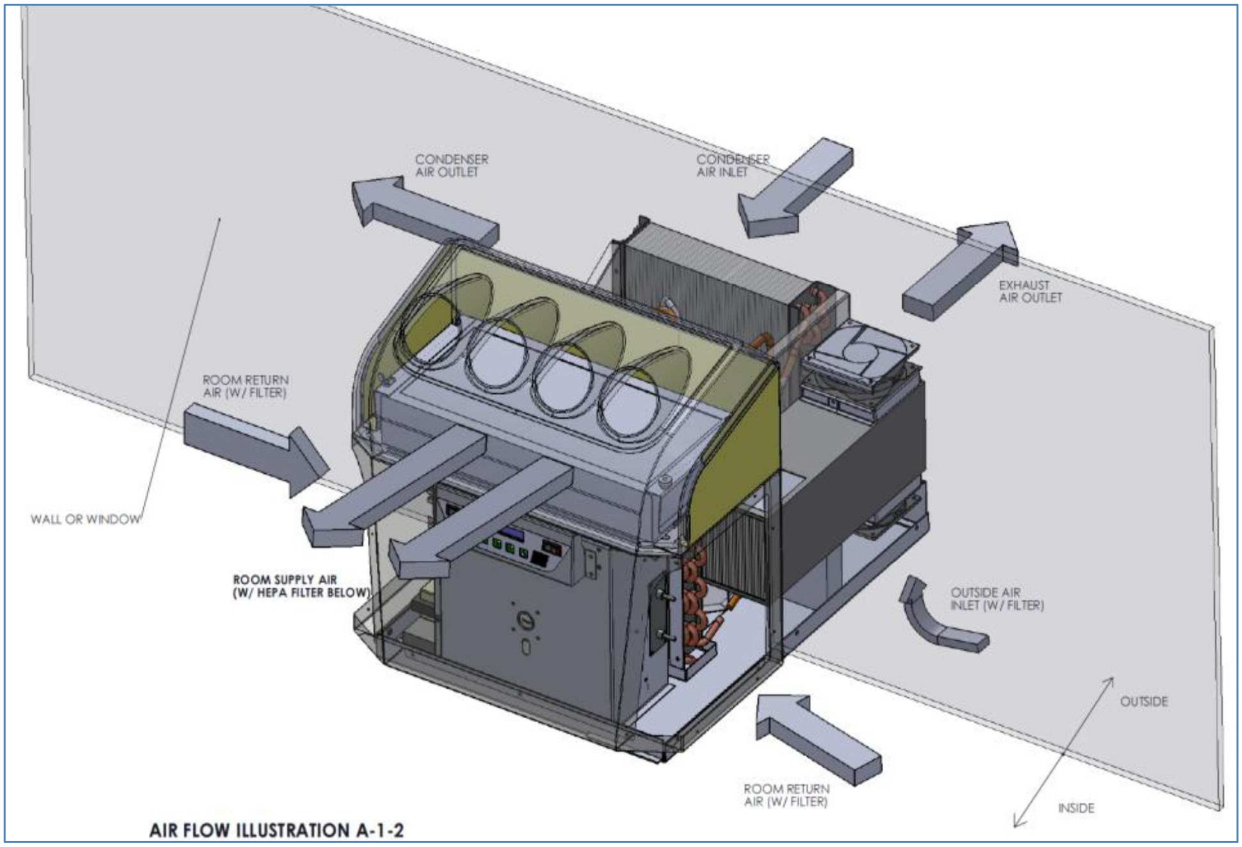


Figure 3. Airflow though a HEPAirX ventilating room air purifier (source:http://airinnovations.com/).

2.3 Data Cleaning

The first step after gathering the raw data for each home was to clean it by eliminating during times of instrument error. The CPC raw data included the date, time, concentration, counts, absolute pressure, pulse height, pulse STD and status flag. The date, time, concentration and status flag were the parameters used for data analysis on the next step. First, the status flag numbers were essential in eliminating the data that was not useful. Basically, the status flag determined if the CPC has measured the concentrations accurately.

The next step was to match the dates from the CPC and flow censor (measuring voltage). For this step, I created two more columns in excel for HOBO data, time and voltage. The date and time of CPC was matched with the corresponding date and time for HOBO after some additional effort. The flow sensor sent out different voltage signals depending on if the flow was in the line or not. Table 2 categorizes different participant weekly data for Boston.

Table 2. Weekly data categorization for Boston participants.

Table. categories of participants for data proccessing														
	PR01	PR02	PR03	PR04	PR05	PR06	PR07	PR08	PR09	PR10	PR11	PR12	PR13	PR14
Flow sensor functions normal	wk1, wk2, wk3, wk4, wk6	wk1, wk2, wk3, wk6	wk3, wk4,wk6	wk1,wk2, wk4, wk6	wk3, wk2, wk6	wk1, wk2, wk3, wk6	wk1, wk2, wk3, wk4, wk5, wk6	wk1, wk5	wk1, wk2, wk3	wk1, wk3, wk4, wk5, wk6		wk1, wk2	wk1, wk3	wk2
flow sensor functions partially normal	wk5	wk4, wk5	wk2, wk5	wk3	wk1, wk5	wk4, wk5		wk2, wk3, wk4, wk6	wk4	wk2	wk1, wk2, wk6	wk3	wk2, wk4, wk5, wk6	wk1, wk3, wk4, wk5
flow sensor doesn't work at all			wk1								wk3, wk4, wk5	wk4, wk5, wk6		wk6
CPC malfunction		wk4	wk1, wk2, wk3, wk4	wk5	wk2	wk1, wk5	wk3, wk4	wk1, wk2	wk2, wk5, wk6	wk1, wk2, wk3, wk4, wk5, wk6	wk1, wk2,wk3	wk4, wk6	wk2, wk4, wk5, wk6	
No errors in CPC	wk2, wk3, wk4, wk5, wk6	wk1, wk2, wk3, wk5,wk6	wk5, wk6	wk1, wk2, wk4, wk6	wk1, wk3, wk5, wk6		wk1,wk2, wk5,wk6	wk3, wk4, wk5, wk6	wk1, wk3, wk4		wk4, wk5, wk6	wk1, wk2, wk5	wk3	wk1, wk2, wk3, wk4, wk5, wk6

2.4 Data processing

After data cleaning the data were processed by separating the indoor and outdoor air measurements. For each participant we have three weeks of HEPA filter and three weeks of sham filter data. For separating the indoor and outdoor air components for a large data set, different codes were written. For some weeks the voltage readout did not match the CPC data; therefore, the timer had to be used for data processing.

Figure 4, the blue line is showing the voltage variation through time. Either the highest level or the lowest level in the blue line variation would be associated with outdoor or indoor air. The red line is the general trend of the indoor and outdoor air concentrations. The green line is the outdoor concentration and the purple line would be the indoor concentration. This is a best-case scenario for determining when measured PNC is either indoors or outdoors.

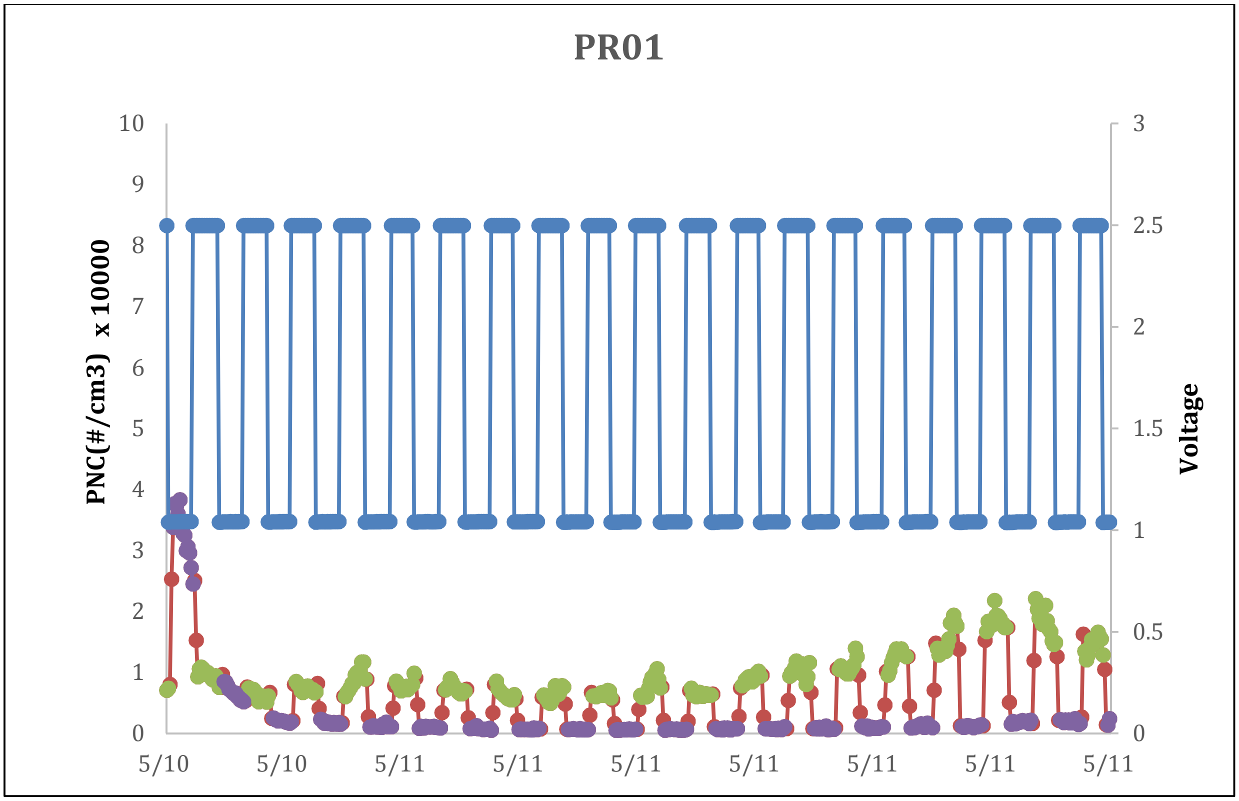


Figure 4. Demonstration of the raw data after running the code for indoor and outdoor data separation.

After making sure that the indoor and outdoor concentration data had been processed correctly, the trend for indoor and outdoor temporal variation is shown. Figure 5 demonstrates the variation of indoor and outdoor concentration for PR01 for week 1. The section with CPC errors is when the instrument had problems and stopped functioning.

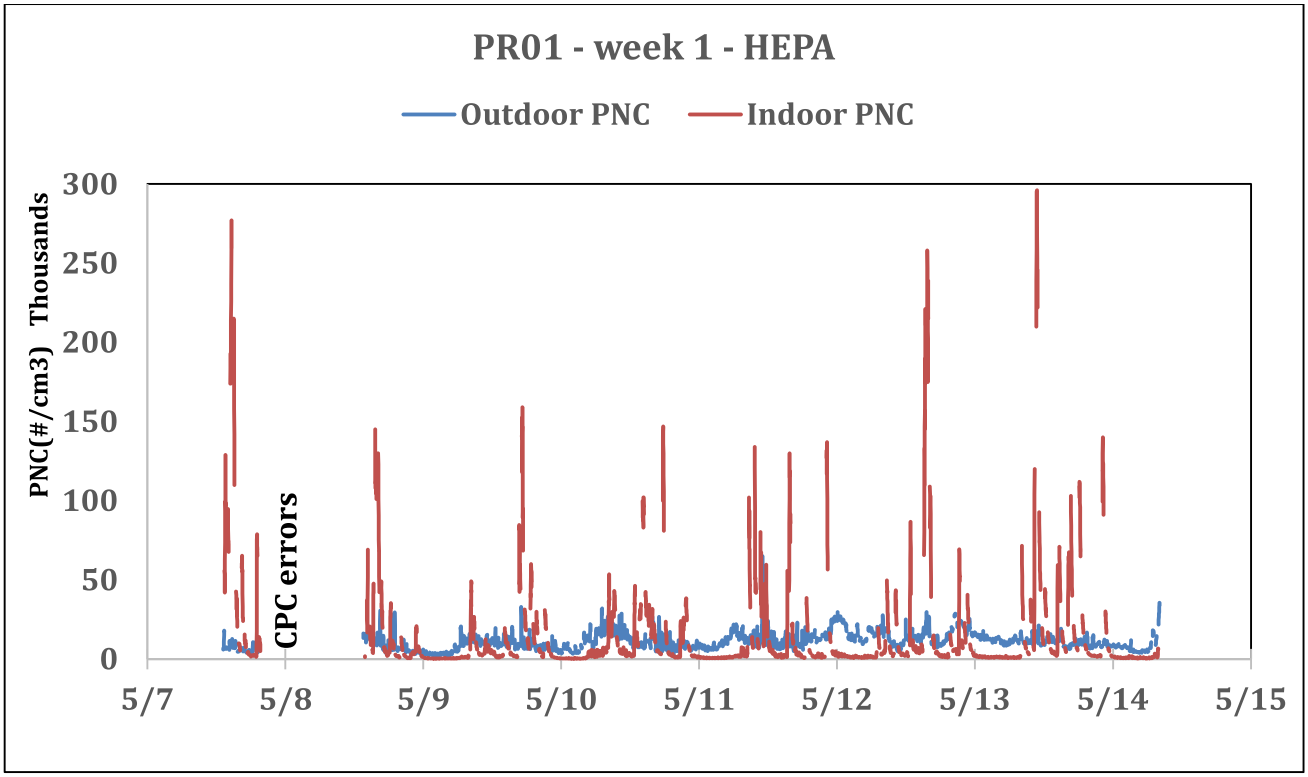


Figure 5. Indoor and outdoor PNC variations for PR01 during week one. The red line is the indoor and the blue line is the outdoor air.

The data for the rest of the weeks for PR01 and other participants are shown in the supplementary section.

Table 3 demonstrates the available usable data for each home in Boston. PR09 is shown to have the most usable data; however, it is estimated that all the data gathered for PR09 are all indoor data due to instrument malfunction.

Table 3. Usable data for Boston participants.

Percent Usable Data									
Boston Homes	wk1	wk2	wk3	wk4	wk5	wk6	HEPA data available	SHAM data available	overall usable data
PR01	76.80%	93.30%	51.40%	86.60%	84.70%	86.60%	70.20%	85.90%	77.00%
PR02	87.70%	82.90%	87.10%	71.40%	87.60%	86.70%	82.00%	85.90%	84.00%
PR03	87.20%	26.20%	4.78%	43.20%	86.40%	21.50%	37.90%	51.40%	44.40%
PR04	86.70%	86.70%	86.70%	86.70%	86.60%	86.60%	86.70%	86.70%	86.70%
PR05	86.60%	24.90%	86.50%	86.70%	86.70%	86.70%	67.30%	86.70%	77.50%
PR06	92.70%	94.00%	94.00%	92.40%	91.40%	93.30%	92.10%	93.50%	92.80%
PR07	86.60%	93.30%	53.50%	93.20%	93.30%	93.30%	93.30%	74.50%	84.50%
PR08	93.40%	83.60%	87.90%	91.50%	94.00%	87.80%	91.10%	88.30%	89.70%
PR09	93.30%	100.00%	93.30%	93.30%	93.30%	93.30%	93.30%	95.50%	94.40%
PR10	93.90%	88.90%	93.90%	93.90%	93.90%	94.00%	92.10%	93.90%	93.10%
PR11	87.10%	88.90%	86.90%	87.00%	87.00%	93.40%	87.30%	88.90%	88.00%
PR12	93.30%	92.70%	90.30%	82.00%	79.80%	70.60%	78.00%	92.30%	85.20%
PR13	21.30%	73.70%	94.00%	94.00%	94.00%	92.50%	60.70%	93.20%	77.00%
PR14	94.10%	93.30%	87.50%	93.30%	85.50%	79.90%	86.90%	92.50%	89.70%

PR03 has the lowest overall usable data due to CPC malfunction and the flow sensor's partial functioning as it has been shown in Table 1.

Table 4 illustrates the percentage data available for Chelsea participants. PR16 has the lowest available usable data. Week one has the lowest percentage, which affects the overall percentage. This is due to the fact that during wk1 there is no good voltage data at all. Therefore, the indoor and outdoor PNC concentration separation has been done based on other PR's patterns.

Table 4. Usable data for Chelsea participants.

Percent Usable Data									
Chelsea Homes	wk1	wk2	wk3	wk4	wk5	wk6	total HEPA data available	total SHAM data available	overall usable data
PR16	33.80%	85.60%	94.00%	90.00%	78.20%	94.00%	70.10%	87.60%	78.90%
PR17	51.40%	93.50%	93.40%	92.00%	92.00%	93.50%	92.50%	77.00%	84.70%
PR19	94.00%	87.30%	87.30%	89.80%	87.20%	94.00%	90.30%	89.50%	89.90%
PR20	93.50%	93.50%	93.50%	93.50%	93.40%	93.50%	93.50%	93.50%	93.50%
PR21	93.30%	93.30%	93.30%	93.50%	83.70%	93.30%	89.60%	93.30%	91.40%
PR22	93.50%	93.50%	93.50%	93.50%	93.00%	85.00%	92.00%	93.50%	92.70%
PR23	93.30%	93.20%	93.30%	86.10%	80.00%	80.00%	93.30%	82.00%	87.50%
PR24	93.50%	93.40%	93.50%	93.50%	91.40%	83.70%	93.50%	89.60%	91.60%
PR25	82.50%	80.40%	80.00%	80.00%	80.00%	83.70%	93.30%	81.10%	83.20%
PR26	93.50%	83.80%	83.80%	89.70%	82.00%	82.00%	87.60%	85.00%	86.30%

2.5 Data Analysis

Next step after data processing was to obtain median hourly concentrations during HEPA and sham for outdoor and indoor. Since we had 30-sec average concentrations and 1-min average concentrations, the median was calculated for each hour. Afterwards, I imported the data into Sigma plot software to graphically present the data. For comparison boxplots and for each participant weekly variation were obtained using straight-line plots. For the sake of comparison, the y-axis was adjusted so that for some boxplots, the upper extreme could not be visible; however, for most of them, the whisker and upper extreme is visible. To obtain monthly variations, all the data of Boston participants were pooled together and were separated by month. Seasonal variations were obtained by the same strategy, but the separation was based on season. These processes were all done for Chelsea participants too.

3.0 Results

3.1. Descriptive statistics

Each participant's data has been separated for HEPA outdoor, HEPA indoor, sham outdoor and sham indoor. The number of PNC measurements, missing data, the mean, standard deviation, range, minimum and maximum, and median concentration and other descriptive statistics are shown in Tables 5 (Boston) and 6 (Chelsea).

A number of observations can be made from Tables 5 and 6. One of them is that, the maximum of indoor HEPA filter measurements is higher than outdoor HEPA in terms of particle number concentration. The highest maximum being 10 times higher for participant 13; however, the lowest maximum difference belongs to participant 9.

Table 5. Summary statistics for the 14 participants in Boston.

Participants		HEPA		Sham	
		out	in	out	in
PR01	Data points	6.10E+02	6.10E+02	4.45E+02	4.45E+02
	Median	1.08E+04	4.87E+03	8.80E+03	8.20E+03
	Min - Max	1820 - 46550	297 - 202000	707.5 - 45900	831.5 - 259000
PR02	Data points	4.83E+02	4.83E+02	5.52E+02	5.52E+02
	Median	7.52E+03	1.29E+03	1.12E+04	9.34E+03
	Min - Max	900.5 - 41400	83.8 - 228000	1460 - 61500	158 - 547000
PR03	Data points	5.28E+02	5.28E+02	4.82E+02	4.82E+02
	Median	7.68E+03	3.72E+03	9.29E+03	8.50E+03
	Min - Max	2710 - 22500	1350 - 195000	3255 - 35600	2395 - 386000
PR04	Data points	4.58E+02	4.58E+02	5.99E+02	5.99E+02
	Median	7.25E+03	2.06E+03	8.78E+03	5.50E+03
	Min - Max	1235 - 28800	424 - 267500	2330 - 41050	975 - 445500
PR05	Data points	4.56E+02	4.56E+02	5.06E+02	5.06E+02
	Median	1.00E+04	1.74E+03	1.20E+04	7.34E+03
	Min - Max	2205 - 59200	245.5 - 292000	1070 - 78400	1405- 726500
PR06	Data points	4.81E+02	4.81E+02	5.05E+02	5.05E+02
	Median	1.33E+04	1.22E+04	1.76E+04	3.61E+03
	Min - Max	1170 - 60300	2785 - 1438500	3230 - 65000	1570 - 1890000
PR07	Data points	4.75E+02	4.75E+02	5.12E+02	5.12E+02
	Median	8.05E+03	7.35E+03	1.48E+04	1.46E+04
	Min - Max	1750 - 149000	1590 - 223500	3440 - 217000	3040 - 466000
PR08	Data points	4.80E+02	4.80E+02	5.53E+02	5.53E+02
	Median	1.55E+04	3.72E+03	1.93E+04	7.57E+03
	Min - Max	832 - 92250	182 - 182000	1925 - 59850	541 - 305000
PR09	Data points	4.81E+02	4.81E+02	5.29E+02	5.29E+02
	Median	6.46E+02	7.69E+02	3.72E+03	2.82E+03
	Min - Max	70.2 - 17750	79.8 - 21550	159 - 39600	177 - 44450
PR10	Data points	5.03E+02	5.03E+02	5.06E+02	5.06E+02
	Median	1.12E+04	3.56E+03	9.21E+03	5.95E+03
	Min - Max	961 - 58700	370 - 218000	537.5 - 50100	426 - 211000
PR11	Data points	5.77E+02	5.77E+02	5.06E+02	5.06E+02
	Median	7.53E+03	4.80E+03	7.08E+03	4.36E+03
	Min - Max	1060 - 34500	210.5 - 271000	1595 - 46100	470.5 - 133000
PR12	Data points	4.76E+02	4.76E+02	5.33E+02	5.33E+02
	Median	8.75E+03	1.32E+03	7.72E+03	3.05E+03
	Min - Max	1950 - 48400	132 - 100800	1475 - 44250	403 - 121000
PR13	Data points	5.29E+02	5.29E+02	4.82E+02	4.82E+02
	Median	1.06E+04	1.82E+03	9.77E+03	6.60E+03
	Min - Max	3705 - 31500	195 - 458500	1620 - 45400	762 - 558000
PR14	Data points	4.80E+02	4.80E+02	5.06E+02	5.06E+02
	Median	1.41E+04	2.66E+03	1.54E+04	5.37E+03
	Min - Max	2060 - 47750	266 - 160500	1280 - 73300	625.5 - 322500

*The units for Median, Minimum and Maximum are all particles/cm^3

Table 6. Summary statistics for the 10 participants in Chelsea.

Chelsea Participants		HEPA		Sham	
		out	in	out	in
PR16	Data points	5.50E+02	5.50E+02	5.05E+02	5.05E+02
	Median	1.44E+04	1.67E+03	1.25E+04	5.59E+03
	Min - Max	3580 - 58400	115 - 57050	2615 - 82400	940 - 35600
PR17	Data points	5.05E+02	5.05E+02	5.06E+02	5.06E+02
	Median	1.69E+04	2.34E+03	1.59E+04	1.14E+04
	Min - Max	2615 - 95900	344.5 - 365000	5090 - 140500	1635 - 218000
PR19	Data points	5.05E+02	5.05E+02	5.05E+02	5.05E+02
	Median	9.43E+03	9.54E+02	1.06E+04	3.92E+03
	Min - Max	1575 - 82400	56.5 - 341000	1560 - 85350	427 -145500
PR20	Data points	5.06E+02	5.06E+02	5.05E+02	5.05E+02
	Median	1.34E+04	9.12E+02	9.97E+03	3.37E+03
	Min - Max	2620 - 101000	85 - 147000	2250 - 61400	669 - 149000
PR21	Data points	5.05E+02	5.05E+02	4.81E+02	4.81E+02
	Median	8.86E+03	2.00E+03	1.13E+04	4.78E+03
	Min - Max	1965 - 73300	229 - 117000	1795 - 100000	966 - 297500
PR22	Data points	5.02E+02	5.02E+02	5.05E+02	5.05E+02
	Median	5.73E+03	4.67E+02	1.12E+04	3.33E+03
	Min - Max	955 - 29950	61.05 - 200500	2190 - 101000	660 - 354000
PR23	Data points	4.83E+02	4.83E+02	5.06E+02	5.06E+02
	Median	8.49E+03	1.06E+03	7.85E+03	4.26E+03
	Min - Max	1200 - 106000	57.3 - 105500	1310 - 67300	592 - 312000
PR24	Data points	5.07E+02	5.07E+02	5.04E+02	5.04E+02
	Median	1.36E+04	3.74E+03	1.08E+04	5.44E+03
	Min - Max	955.5 - 74750	66.2 - 247000	890 - 81600	222 - 61800
PR25	Data points	5.31E+02	5.31E+02	5.07E+02	5.07E+02
	Median	1.01E+04	1.92E+03	9.17E+03	4.87E+03
	Min - Max	1120 - 86800	220.5 - 166000	986 - 119000	428 - 230000
PR26	Data points	5.33E+02	5.33E+02	4.80E+02	4.80E+02
	Median	1.37E+04	3.50E+03	1.34E+04	5.73E+03
	Min - Max	2790 - 146000	367 - 135000	2745 - 106000	932 - 292000

*The units for Median, Minimum and Maximum are all particles/cm^3

For PR01, the mean outdoor HEPA and sham are 24 and 21 percent lower than the corresponding indoors values; while the median outdoor HEPA and sham are 58 and 47 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 3 and 21 percent lower than during the sham period.

For PR02, the mean outdoor HEPA and sham is 37 and 59 percent lower than the corresponding indoors values; while the median outdoor HEPA and sham is 82 and16 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 55 and 86 percent lower than during the sham period.

For PR03, the mean outdoor HEPA and sham is 11 and 87 percent lower than the corresponding indoors values; while the median outdoor HEPA and sham is 51 and 9 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 63 lower and 56 percent higher than during the sham period.

For PR04, the mean outdoor HEPA and sham is 22 higher and 2.2 percent lower than the corresponding indoors values; while the median outdoor HEPA and sham is 71 and 37 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 37 and 62 percent lower than during the sham period.

For PR05, the mean outdoor HEPA and sham is 20 higher and 42 percent lower than the corresponding indoors values; while the median outdoor HEPA and sham is 82 and 39 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 62 and 76 percent lower than during the sham period.

For PR06, the mean outdoor HEPA and sham is 59 and 30 percent lower than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 80 and 79 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 30and 70 percent higher than during the sham period.

For PR07, the mean outdoor HEPA and sham is 13 and 19 percent lower than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 9 and 1 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 38 and 49 percent lower than during the sham period.

For PR08, the mean outdoor HEPA and sham is 48 and 28 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 75 and 60 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 41 percent lower and 50 percent higher than during the sham period.

For PR09, the mean outdoor HEPA and sham is 16 percent lower and 23 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 15 percent lower and 9 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 57 and 72 percent lower than during the sham period.

For PR10, the mean outdoor HEPA and sham is 25 percent higher and 26 percent lower than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 68 and 35 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 33 and 40 percent lower than during the sham period.

For PR11, the mean outdoor HEPA and sham is 39 and 5 percent lower than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 36 and 38 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 37 and 9 percent lower than during the sham period.

For PR12, the mean outdoor HEPA and sham is 52 and 14 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 85 and 60 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 27 and 56 percent lower than during the sham period.

For PR13, the mean outdoor HEPA and sham is 51 and 66 percent lower than the correspondent indoors values respectively; while the median outdoor HEPA and sham is 82 and 32 percent higher than the correspondent indoor values. The mean and median indoor levels of HEPA are 29 and 72 percent lower than during the sham period.

For PR14, the mean outdoor HEPA and sham is 33 and 0.6 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 81 and 65 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 64 and 50 percent lower than during the sham period.

For PR16, the mean outdoor HEPA and sham is 84 and 52 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 88 and 55 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 65 and 70 percent lower than during the sham period.

For PR17, the mean outdoor HEPA and sham is 46 and 18 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 86 and 28 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 38 and 79 percent lower than during the sham period.

For PR19, the mean outdoor HEPA and sham is 78 and 54 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 89 and 63 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 58 and 75 percent lower than during the sham period.

For PR20, the mean outdoor HEPA and sham is 53 and 7 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 93 and 66 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 25 and 72 percent lower than during the sham period.

For PR21, the mean outdoor HEPA and sham is 22 percent lower and 9 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 77 and 57 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 14 and 58 percent lower than during the sham period.

For PR22, the mean outdoor HEPA and sham is 84 percent higher and 15 percent lower than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 91 and 70 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 75 and 85 percent lower than during the sham period.

For PR23, the mean outdoor HEPA and sham is 37 percent higher and 34 percent lower than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 87 and 45 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 54 and 75 percent lower than during the sham period.

For PR24, the mean outdoor HEPA and sham is 56 and 62 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 72 and 49 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 9 and 31 percent lower than during the sham period.

For PR25, the mean outdoor HEPA and sham is 50 and 0.1 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 80 and 46 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 50 and 60 percent lower than during the sham period.

For PR26, the mean outdoor HEPA and sham is 51 and 7 percent higher than the corresponding indoors values respectively; while the median outdoor HEPA and sham is 74 and 57 percent higher than the corresponding indoor values. The mean and median indoor levels of HEPA are 42 and 39 percent lower than during the sham period

3.2. Weekly variations during HEPA and sham filtration

The median hourly PNC was calculated for each of the participants. The median of 30 1-min averages collected in two 15-minute windows per hour is used as data points in the figures and for each comparison and calculation. The results for PR01 to PR14 for Boston and PR16 to PR24 for Chelsea are shown in Figures 6 and 7.

Figure 6 illustrates the weekly variations for PR01 during the HEPA filter data measurements. There are at least one or two small spikes in the outdoor level of PNC during each day which may be due to traffic and rush hours; however, in the indoor weekly variation there are spikes higher than 10^5 particles/cm^3. During weeks one and two of indoor measurement, the second spike in the day, which is around dinner time, is constantly higher that the first spike. This may be due to indoor activity especially cooking. Moreover, as this trend is continuous during each day, this emphasizes the influence of cooking on number concentration. During week three of indoor air data there are fewer spikes compared to week one and two. This may be due to different reasons such as the indoor activity may differ or the food being cooked varies or it may be a contribution of outdoor PNC due to open windows.

Figure 7 illustrates the weekly variation for PR01 during the three weeks sham measurements for indoor and outdoor. There are low indoor levels during the sham period that may be highly correlated to outdoor measurement. Table 7 illustrates the use of other ACs and the locations of the extra AC with information about open windows. Only a few of the participant's information are reported.

Table 7. Information about AC & open windows.

PR	AC/location of AC	Open windows
1	yes/ another room other than HEPA	----
2	yes/ another room other than HEPA	----
3	yes/ same room as HEPA	occasionally in the bedroom & living room
4	yes/ another room other than HEPA	always in the kitchen
5	No	----
6	yes/ another room other than HEPA	----
7	----	----
8	No	No
9	No	No
10	No	Occasionally in the kitchen
11	yes/ another room other than HEPA	Occasionally in the living room
12	yes/ central air above HEPA unit	Occasionally in the living room
13	No	No

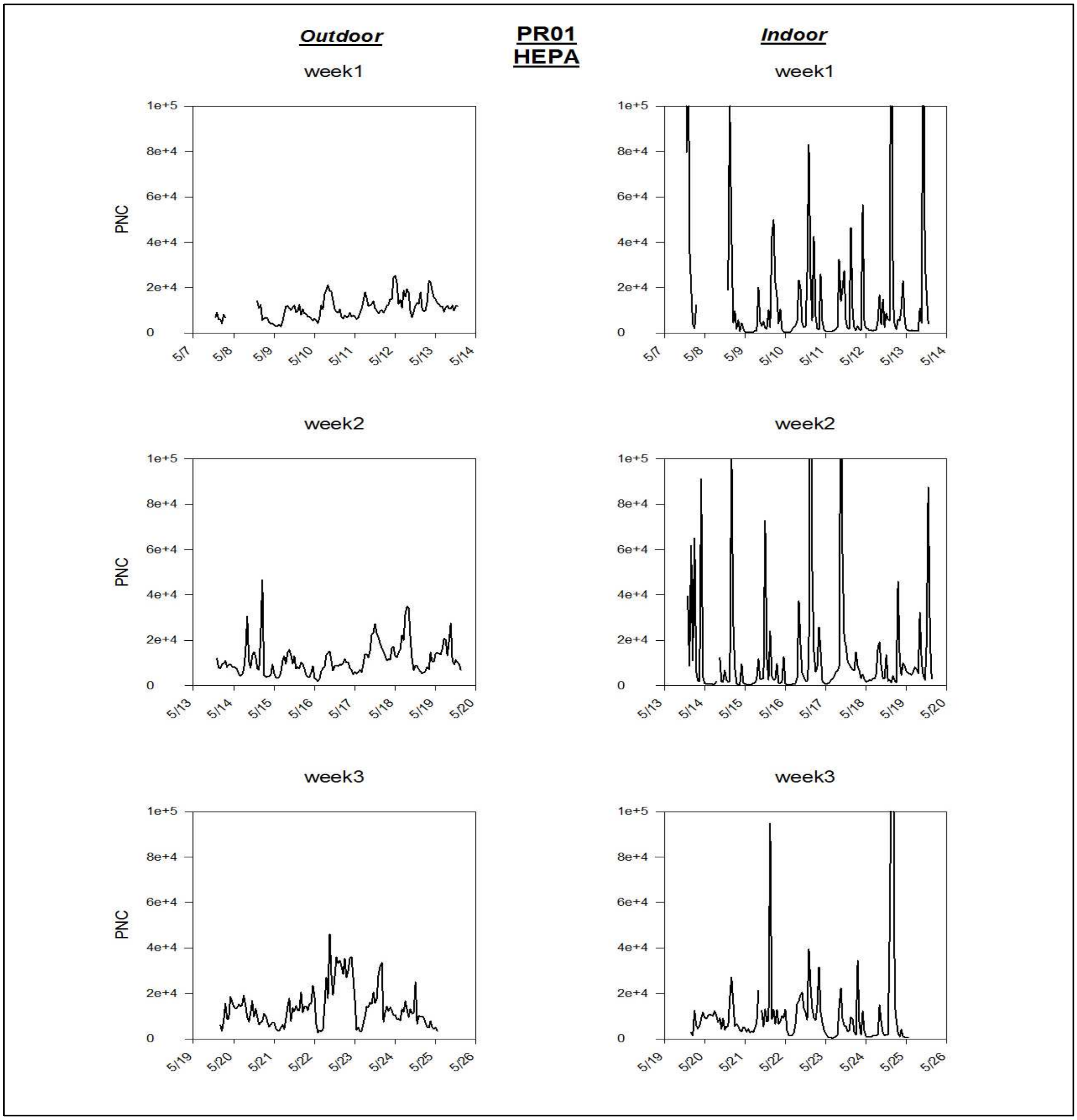


Figure 6. Weekly variations of PNC levels for outdoors and indoors during HEPA filtration for PR01**.**

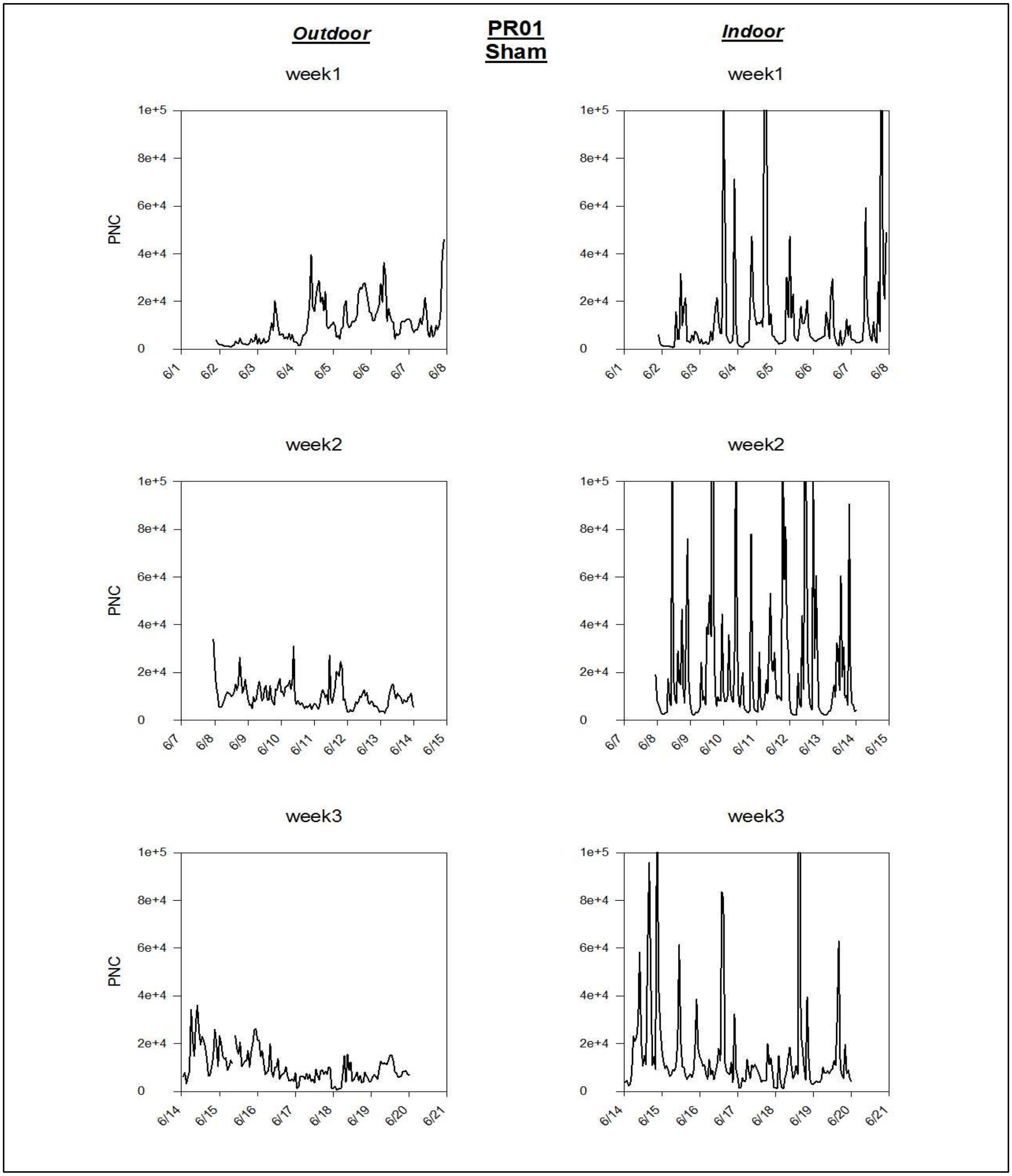
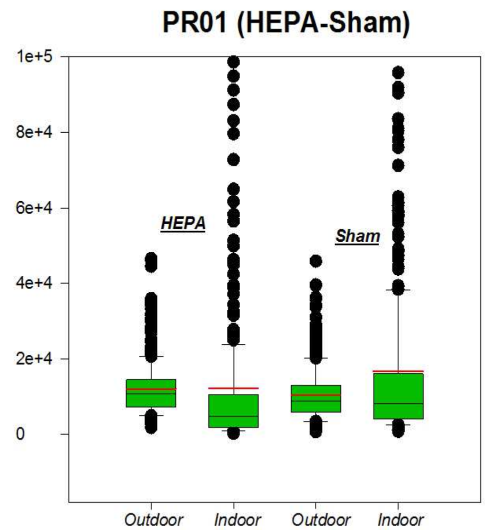


Figure 7. Weekly variations of PNC levels for outdoors and indoors during sham filtration for PR01.

3.3. Comparison of HEPA vs. sham filtration

Figure 8 illustrates the distribution of PNC during outdoor and indoor measurements for HEPA and sham filtration for PR01. The red line is the mean and the black line in the boxes is the median. The mean indoor concentrations during HEPA measurement for indoor and outdoor are approximately the same as sham measurements; however, the median for outdoor is higher than indoor. It may be concluded that we have more very high PNC spikes during the indoor measurement causing an increase in the mean relative to the median. This is true for the outdoor and indoor concentration during the sham period. In the other graph in Figure 8, the mean and median during outdoor measurement for HEPA and sham are approximately the same. The 95th percentile, median and mean during the HEPA are all lower than the sham period. The highest concentration level is during the sham period and it goes until 300,000 (#/cm3) and the highest outdoor level goes until 50,000 (#/cm3). The outdoor concentrations during the six weeks look approximately the same, which would be a better situation for comparing the indoor concentrations during each three weeks; comparing parameters such as the influence of building type, indoor activity, efficiency of HEPA filter and open windows and doors.



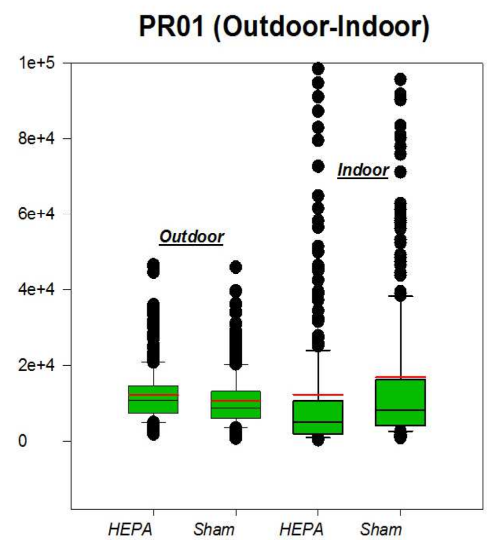


Figure 8. Comparison between outdoor and indoor variations during HEPA and sham filtrations for PR01.

Figures 15, 16 and 17 in the appendices show the results for PR02. The plots show that the mean of the indoor and outdoor PNC during HEPA and sham are both higher than their correspondent outdoor mean and median; however, the median concentrations of both indoor measurements are lower than their outdoor mean and median. The high levels indoors during the six weeks affect the mean while the median is mostly unaffected. The highest level of PNC is observed during the indoor sham measurements and is around 600,000 (#/cm^3); however, both outdoor concentrations are less than 100,000 (#/cm^3).

Figures 18, 19 and 20 in the appendices show the results for PR03. The plots show that the mean of the indoor and outdoor PNC during HEPA and sham are both higher than their corresponding outdoor mean and median as the same for participant one; the median levels are both lower a little than their correspondent outdoor levels. The closeness between the medians of outdoor and indoor may be due to open windows or high levels of indoor activity. The highest concentration level is still for indoor sham and is around 400,000 (#/cm^3). During the HEPA period, we observe higher values which are close to sham period higher values. This observation would make us assume that open windows or HEPA filter malfunction have affected the results.

Figures 21, 22 and 23 in the supplementary section illustrates information for PR04, the mean and median of indoor HEPA is lower than its corresponding outdoor levels; On the other hand, the mean of indoor sham is approximately the same as outdoor sham levels while the median is still lower than the outdoor levels. The highest level of PNC is still for the sham period around 500,000 (#/cm3), while indoor HEPA levels have high levels as of sham indoor levels.

Figures 24, 25 and 26 in the supplementary section illustrates information for PR05, the mean and median of indoor HEPA are lower than their correspondent outdoor levels; On the other hand, the mean of indoor sham is much higher than outdoor sham levels while the median is still lower than the outdoor levels. This high level of mean indoor sham is due to very high levels of PNC affecting the mean. Outdoor sham has higher mean, median and higher range compared to outdoor HEPA; which might be a factor affecting such high levels of indoor sham during that time. The highest level of PNC is still for the sham period around 800,000 (#/cm3), while indoor HEPA have as high levels as sham indoor; However, the quality and quantity of indoor HEPA indoor is less than sham indoor.

Figures 27, 28 and 29 in the supplementary section illustrates information for PR06, the mean HEPA indoor and sham indoor are both higher than the mean and median of their correspondent outdoor levels; However, the HEPA indoor is much higher than outdoor HEPA and even mean and median indoor sham. HEPA indoors has a higher range compared to sham indoors, while their out of range values are approximately as high as each other. The highest PNC value during this time belongs to sham indoor and is approximately about 2,000,000 (#/cm3).

These high levels of HEPA indoor may be due to high indoor activities, filter malfunction or open doors.

Figures 30, 31 and 32 in the supplementary section illustrates information for PR07, the mean HEPA and sham indoor are higher than their outdoor levels; However, the median of indoor HEPA and sham are both approximately the same and maybe lower than their outdoor HEPA and sham. This is due to higher range with higher levels of indoors, which has caused a lift to the levels of medians for indoors making it close to outdoor levels. Indoor HEPA is lower than sham indoor as expected. The highest levels belong to indoor sham approximately around 400,000 (#/cm3). We observe high ranges from outdoor HEPA and sham which might have an influence of the levels if indoor PNC.

Figures 33, 34 and 35 in the supplementary section illustrates information for PR08, the mean and median indoor HEPA and sham are both lower than their outdoor levels; However, the mean for both indoor HEPA and sham are higher than their 95^{th} percentile. This is due to high numbers of high levels of PNC during indoor measurement. The mean and median indoor HEPA is lower than sham indoor levels as expected. The highest level is around 350,000 (#/cm3) and it belongs to sham indoor; however, we observe high level out of range values for both HEPA and sham indoor.

Figures 36, 37 and 38 in the supplementary section illustrates information for PR09, the mean and median indoor HEPA is a little higher than outdoor HEPA. This is due to high numbers of high level concentrations. Outdoor sham is very higher in range, mean, median than outdoor HEPA. This home has had instrument malfunction and all the data is suspected to be indoor data.

Figures 39, 40 and 41 in the supplementary section illustrates information for PR10, the mean indoor sham is higher than the outdoor level; However, the median for both indoor HEPA and sham is lower than their outdoor levels as it should be. Moreover, the indoor HEPA median and mean are both lower than indoor sham as it should be. We observe high levels of outdoor high levels compared to the previous participants. The highest PNC level belongs to HEPA indoor around 250,000 (#/cm3), while sham indoor had high levels as much.

Figures 42, 43 and 44 in the supplementary section illustrates information for PR11, the mean HEPA indoors is higher than outdoor HEPA and sham indoor levels. This is due to the fact that we have high levels of PNC and higher 95^{th} percentile in the indoor HEPA measurements; while the median indoors are all lower than the outdoors and the median indoor HEPA is lower than the median indoor sham as it is supposed to be.

Figures 45, 46 and 47 in the supplementary section illustrates information for PR12; we have both lower levels of mean and median in indoors compared to their correspondent outdoor level. Moreover, indoor HEPA has lower mean and median compared to indoor sham; However, the mean line for indoor HEPA is on the 95th percentile while for indoor sham is higher than the 95th percentile. This concludes that we have very high levels in indoor concentration for both indoor HEPA and sham. The highest level belongs to indoor sham and is around 100,000 (#/cm3) which is lower than the highest values from the previous participants.

Figures 48, 49 and 50 in the supplementary section illustrates information for PR13; the mean indoor HEPA and sham are both higher than the mean of their outdoor levels. Outdoor sham has higher range especially in the high levels compared to outdoor HEPA. The highest number concentration belongs to sham indoors and it around 600,000 (#/cm3). There is a huge amount of high indoor levels causing the mean of both indoor HEPA and sham exceed their 95th percentile.

Figures 51, 52, 53 in the supplementary section illustrates information for PR14; this one has the same trend as participant thirteen for indoor levels except that the mean levels indoors doesn't exceed their correspondent outdoor levels. Moreover, the indoor HEPA range is much lower than sham indoors. Outdoor sham is higher in higher levels while still having the same median and mean as outdoor HEPA. The highest concentration belongs to indoor sham and is around 350,000 (#/cm3).

Figures 54, 55 and 56 in the supplementary section illustrates information for PR16; the mean and median indoor levels are both lower than their correspondent outdoor levels. We have lower ranges for both HEPA and sham. The highest number concentration belongs to sham outdoors around 100,000 (#/cm3). Indoor HEPA is lower than indoor sham as it is supposed to be. As far, this is the participant who has the lowest ranges among other participant. This may be due to very low indoor activity causing this level of number concentration.

Figures 57, 58 and 59 in the supplementary section illustrates information for PR17; the mean and median indoor levels are both lower than their correspondent outdoor levels. The mean indoor HEPA is quite out of range of the 95^{th} percentile. We have the highest level belonging to indoor HEPA and around 400,000 (#/cm3).

Figures 60, 61 and 62 in the supplementary section illustrates information for PR19; the mean and median of Indoor HEPA and sham are both lower than their outdoor levels. Lower range in indoor levels is observed compared to the previous participants. It appears we have little data for Indoor HEPA compared to sham indoors. The highest concentration value belongs to HEPA and sham outdoors which is around 100,000 (#/cm3). This low level of indoor values may be due to very low levels of indoor activity.

Figures 63, 64 and 65 in the supplementary section illustrates information for PR20; the mean and median of Indoor HEPA and sham are both lower than their outdoor levels; However, the mean of indoor HEPA and sham is higher than the 95th percentile. We have high indoor levels both during indoor HEPA and sham. The highest concentration belongs to both indoor HEPA and sham which is around 160,000 (#/cm3). High outdoor levels may have an impact on high levels of indoor concentration.

Figures 66, 67 and 68 in the supplementary section illustrates information for PR21; the mean and median of indoor sham is lower than their outdoor level; however, the mean of indoor HEPA is higher than the 95th percentile and also higher than the mean and median of its outdoor data. We have high indoor levels both during indoor HEPA and sham. The highest concentration belongs to indoor sham which is around 350,000 (#/cm3). This participant does have very high levels for indoor HEPA compared to indoor sham.

Figures 69, 70 and 71 in the supplementary section illustrates information for PR22; the mean of indoor HEPA is higher than the 95th percentile, meaning we have high levels of indoor HEPA concentration. We don’t have a very clear range in indoor HEPA levels. The highest level is for indoor sham and around 400,000 (#/cm3). High outdoor sham values have an effect on the indoor sham levels.

Figures 72, 73 and 74 in the supplementary section illustrates information for PR23; the mean indoor HEPA is lower than its outdoors; however, the mean indoor sham is higher than the mean of outdoor sham. Both the median indoors are lower than their outdoors and indoor HEPA had lower mean and median values as it is supposes to be. The highest value is 350,000 (#/cm3) and belongs to sham indoors.

Figures 75, 76 and 77 in the supplementary section illustrates information for PR24; both the mean and median of indoor HEPA and sham are below the mean and median of their outdoor measurements. Outdoor sham has higher number concentration values compared to outdoor sham. Mean and median of indoor HEPA are both below the mean and median of indoor sham as it is supposed to be. The highest value belongs to indoor HEPA, which has the effect on the mean of indoor HEPA.

Figures 78, 79 and 80 in the supplementary section illustrates information for PR25; both the mean and median of indoor HEPA is below the mean and median of outdoor HEPA. The mean of indoor HEPA is higher than the 95th percentile, emphasizing the existence of small amount of high indoor values during indoor measurements of HEPA. The same trend goes for comparison between outdoor and indoor sham; however, the difference is that the mean indoor sham is as same as the mean outdoor sham. As expected from the mean, the highest values of number concentration belong to indoor sham around 250,000 (#/cm3).

Figures 81, 82 and 83 in the supplementary section illustrates information for participant twenty six; the mean and median of outdoor HEPA are both around the mean and median of indoor HEPA. Mean and median of indoor sham is slightly higher than outdoor sham. There might be indoor activities like cooking affecting the indoor results; however, the highest values belong to indoor sham around 350,000 (#/cm3).

3.4. Boston and Chelsea participants PNC variation during HEPA and sham

Figure 9 demonstrates the variation of PNC among the 14 homes in Boston. The x-axis is the participants. Two boxplots belong to each home; the first one is for HEPA and second one for sham. As it is shown in the indoor PNC variation, the median for indoor sham is higher than indoor HEPA except for participant two and five. Also, from the outdoor variation, for home 7 and 9, the median during HEPA and sham is slightly different, while the outdoor sham being higher than outdoor HEPA. This goes back to the instrument malfunction which affects the data collection and analysis. Moreover, the indoor outdoor ratio for all the participants is below one.

Figure 10 illustrates the same axis for Chelsea participants. The median indoor sham is higher than indoor HEPA for all 10 homes. PR20 and PR22 have slightly different outdoor medians during HEPA and sham compared to rest of the participants.

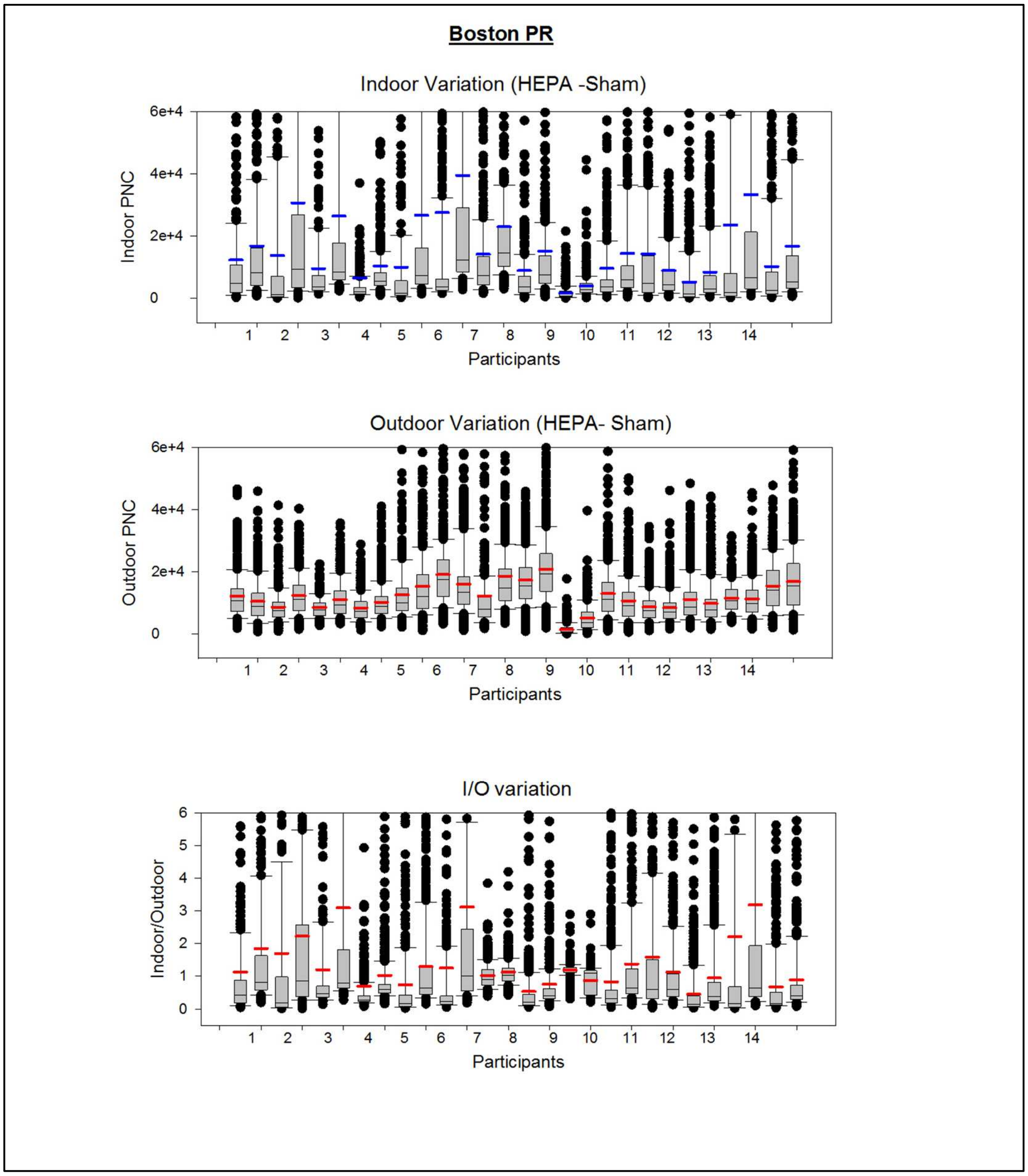


Figure 9. Boxplot of PNC measurements of HEPA and sham filtration in the homes of the 14 Boston participants

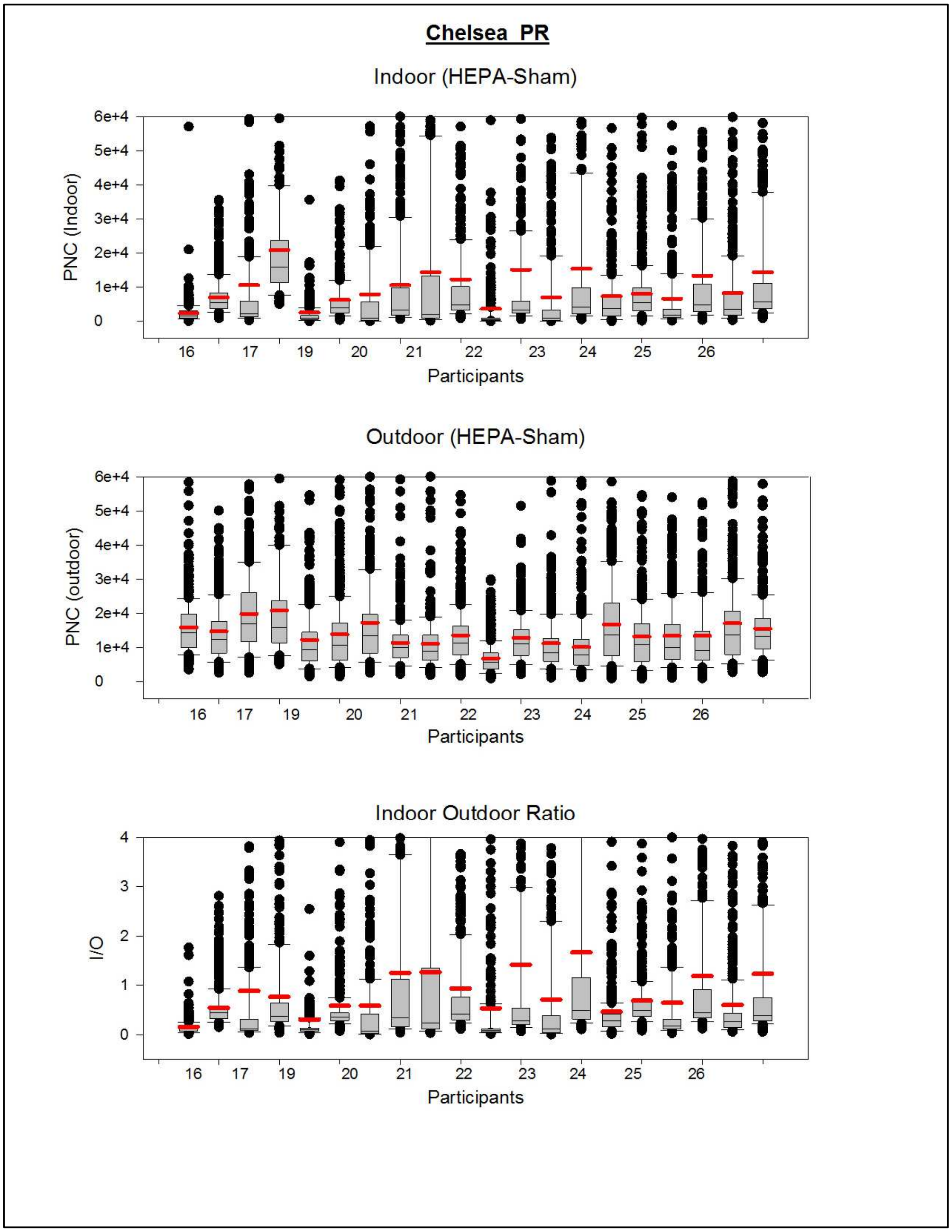


Figure 10. Boxplot of PNC measurements for HEPA and sham filtration in the homes of the 10 Boston participants

3.5. Monthly variations for Boston and Chelsea during sham filtration

Monthly variation of PNC for Boston participants

Figure 11 illustrates outdoor sham monthly variations, indoor sham monthly variations and indoor outdoor ratio variations during the sham period measurements. There is no data for the month of January. The median is about the same during May, June, July and August. After August there is a slight increase in the median as the PNC levels are higher during the cold days. The highest median belongs to December and February. The lowest median PNC is for April.

In the second plot, for indoor sham monthly variations, the mean is higher than the 75th percentile. This may be due to high levels of PNC during indoor activities such as cooking. In all the months the median is around the same number except February and June, which have the highest median. However, it is not expected to see high median in the month of June. This may be due to opened windows and not using air conditioner. Thus, outdoor sham affects the trend in indoor sham.

In the third plot, the indoor outdoor ratio is illustrated by month. The median for all the months is below one. The mean is higher than one for some of the months including March, May, June, July, August and September. This is due to high levels of indoor sham influencing the indoor outdoor ratio. The median for indoor outdoor ratio is highest during February and June and lowest during March and October. Also, under each month, the home number with the number of days in that specific month is included in the parenthesis. For example, for the month of February, home 7 has 21 days of data and home 8 has 18 days of data included.

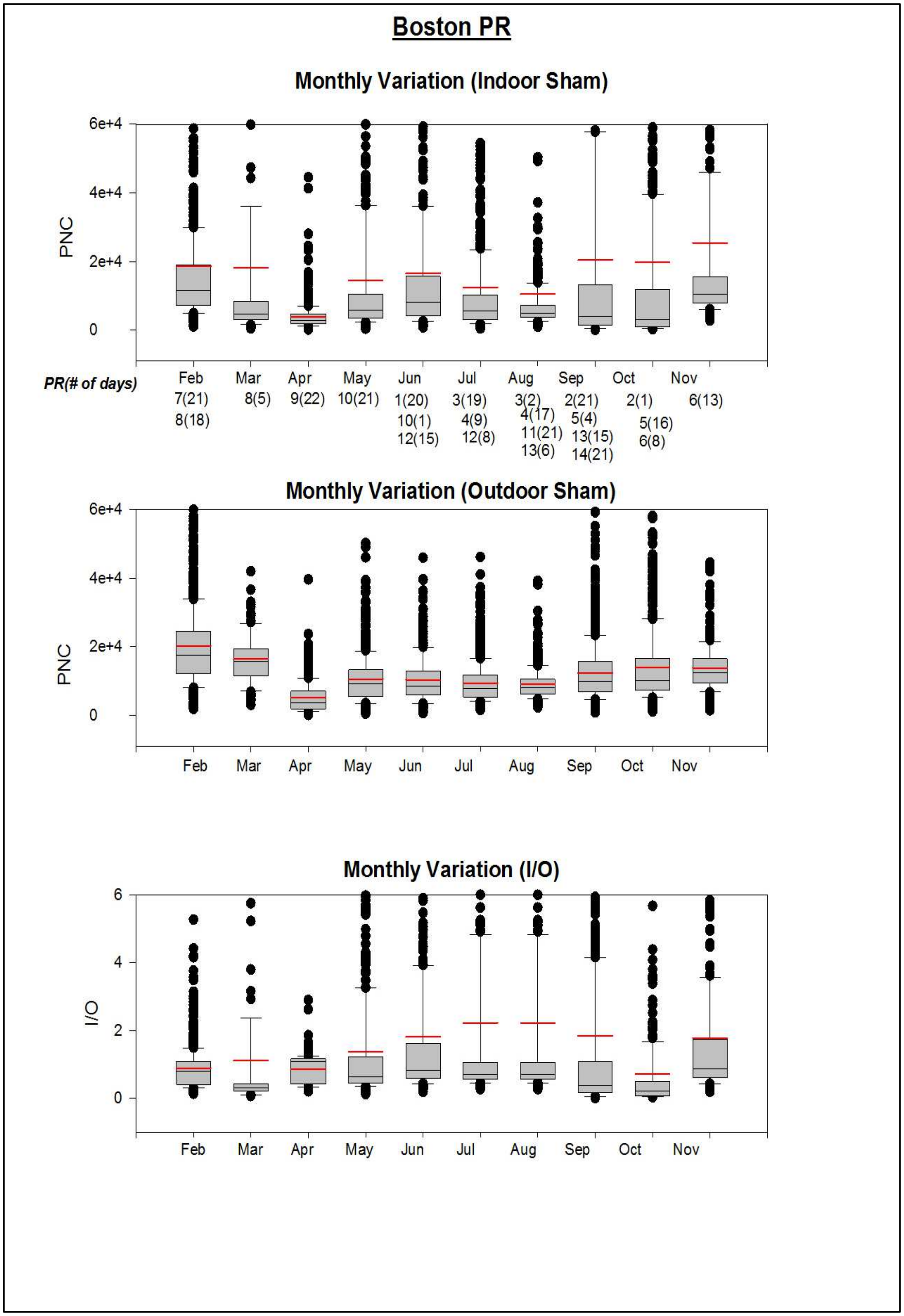


Figure 11. Boxplot of PNC measurements for each month of sham filtration in the homes of the 14 Boston participants

Figure 12 illustrated the monthly for Chelsea participant by month. There is no data in January for any participants. The median for all of the months is approximately the same except for the month of July and November. These months have the highest measurements and higher number of participants included. Therefore, for outdoor sham the data for the month of July and November are not visible because of high values out of range. The highest median sham belongs to cold months especially February and December among other months except for July and November.

In the second plot, the highest median belongs to the month of July for indoor sham measurements. The trend for indoor sham monthly is exactly as the same as Boston participants except for the month of February the median is higher for Boston participants. This may be due to different factors such as number of data, the location and different year's data collection.

In the third plot, the median indoor outdoor ratio for each month is below one; however the mean goes higher than one. The effect of indoor sham concentrations on this ratio is obvious from the mean variation during each month.

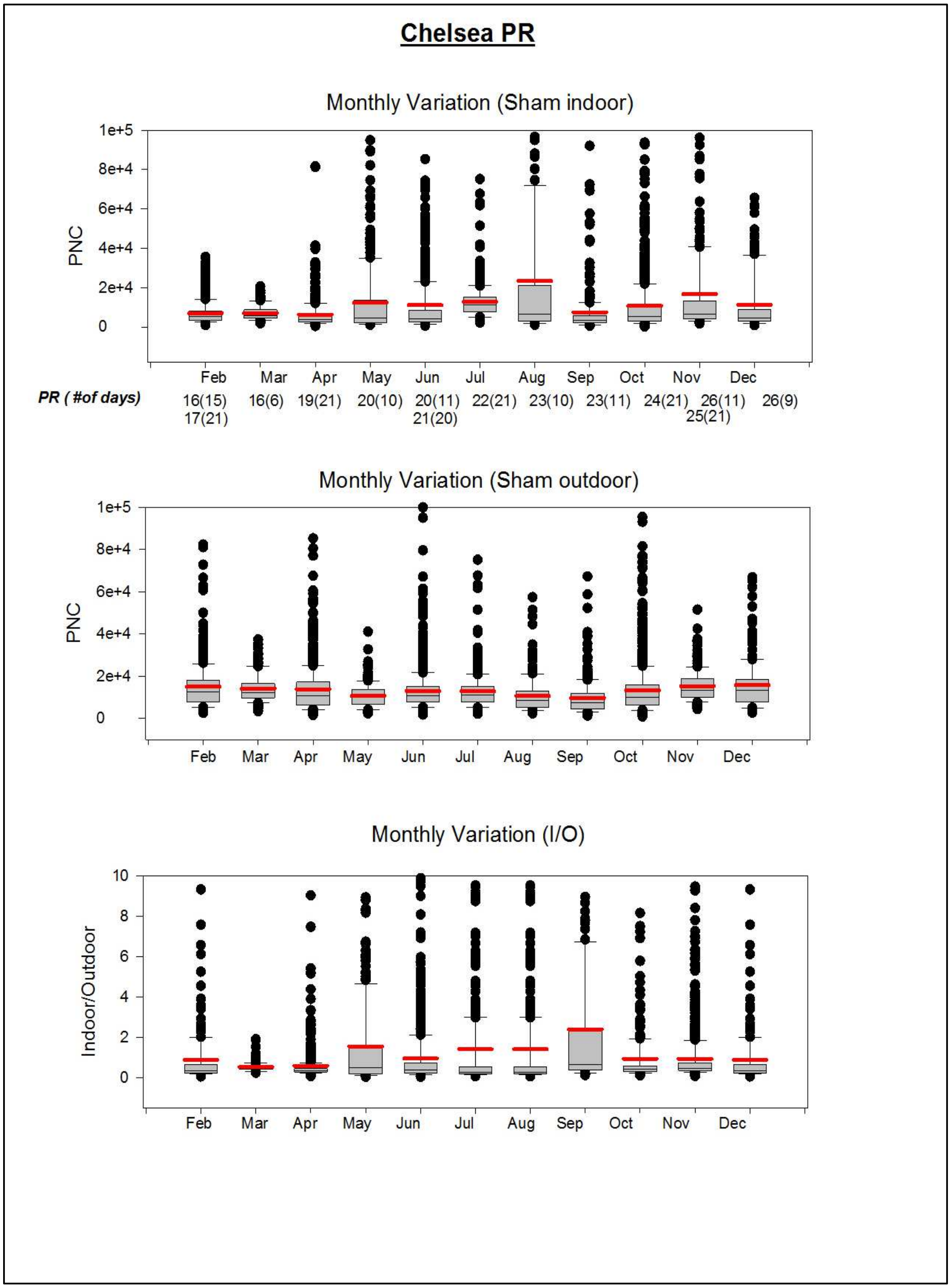


Figure 12. Boxplot of PNC measurements for each month of sham filtration in the homes of the 10 Chelsea participants

3.6. Seasonal variations of Boston and Chelsea homes

Seasonal variation for Boston participants

Figure 13 illustrates the seasonal variation for Boston participants pooled together. The amount of data collected during winter is the least among seasons due to weather conditions and holidays. Outdoor sham between seasons is quite different. Mean and median of outdoor sham during summer and spring is around the same range; however, the mean and median for outdoor sham in fall is higher and in winter is the highest among seasons. This trend fits the indoor sham variations during seasons too, while winter having the highest median and mean among the other seasons during indoor sham measurements.

In Figure 13 the mean indoor sham is higher than the outdoor sham measurements during all seasons. This is due to small number of high levels of particulate number concentration affecting the mean; however, the median is below the median of outdoor measurements.

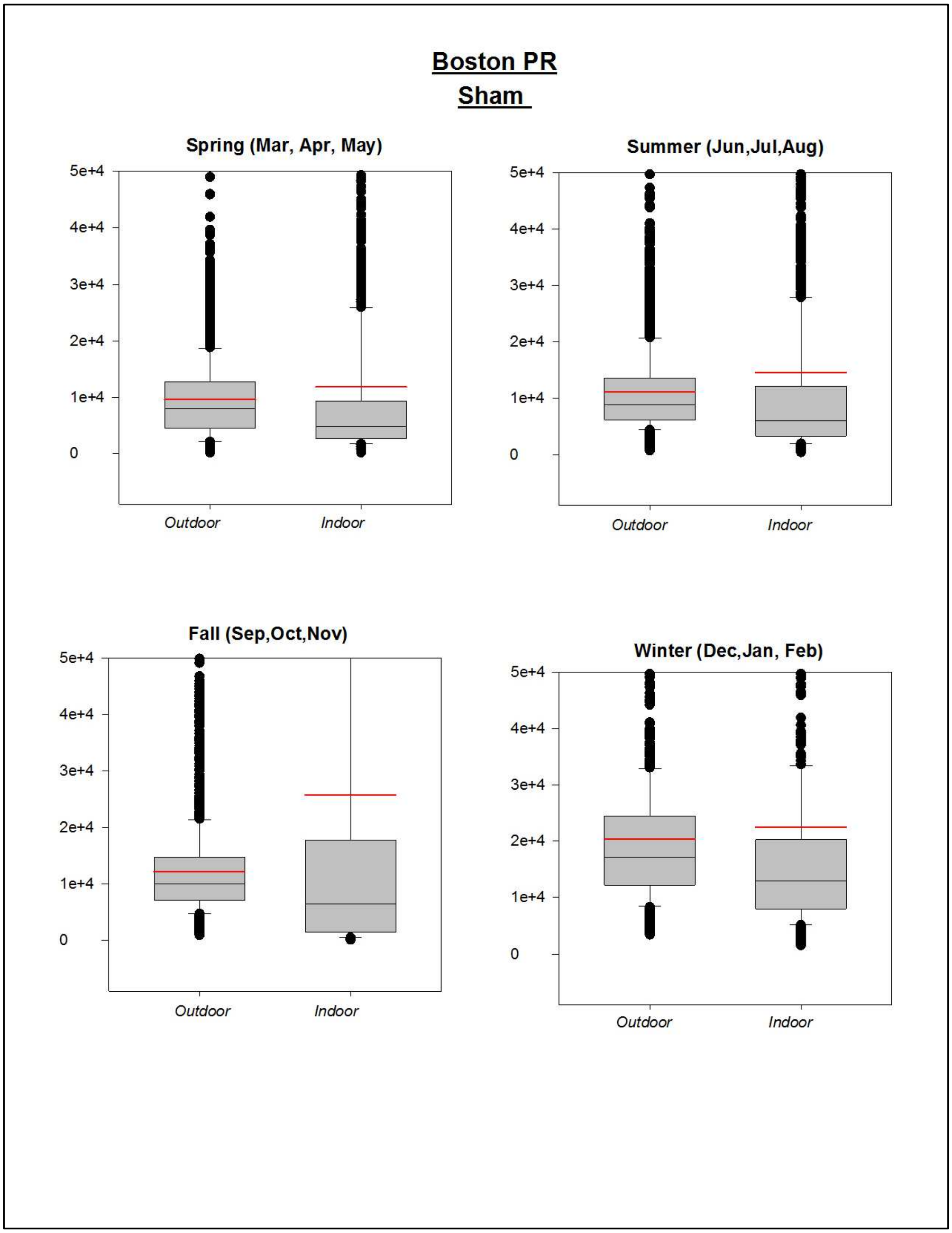


Figure 13. Boxplot of PNC measurements for all 14 Boston participants for each season

Seasonal variations for Chelsea participants

Figure 14 illustrates the seasonal variation during sham for outdoor and indoor variations for Chelsea participants. Outdoor sham has slightly higher values during winter compared to the other seasons. The mean and median of indoor values in all seasons is below than their correspondent outdoor values; however, in summer the mean value for indoor sham is higher than outdoor sham measurements during summer. The median indoor values for all seasons are the same, below 1000 (#/cm3), while due to some high indoor values the mean of indoor sham in summer and fall is higher than 1000 (#/cm3).

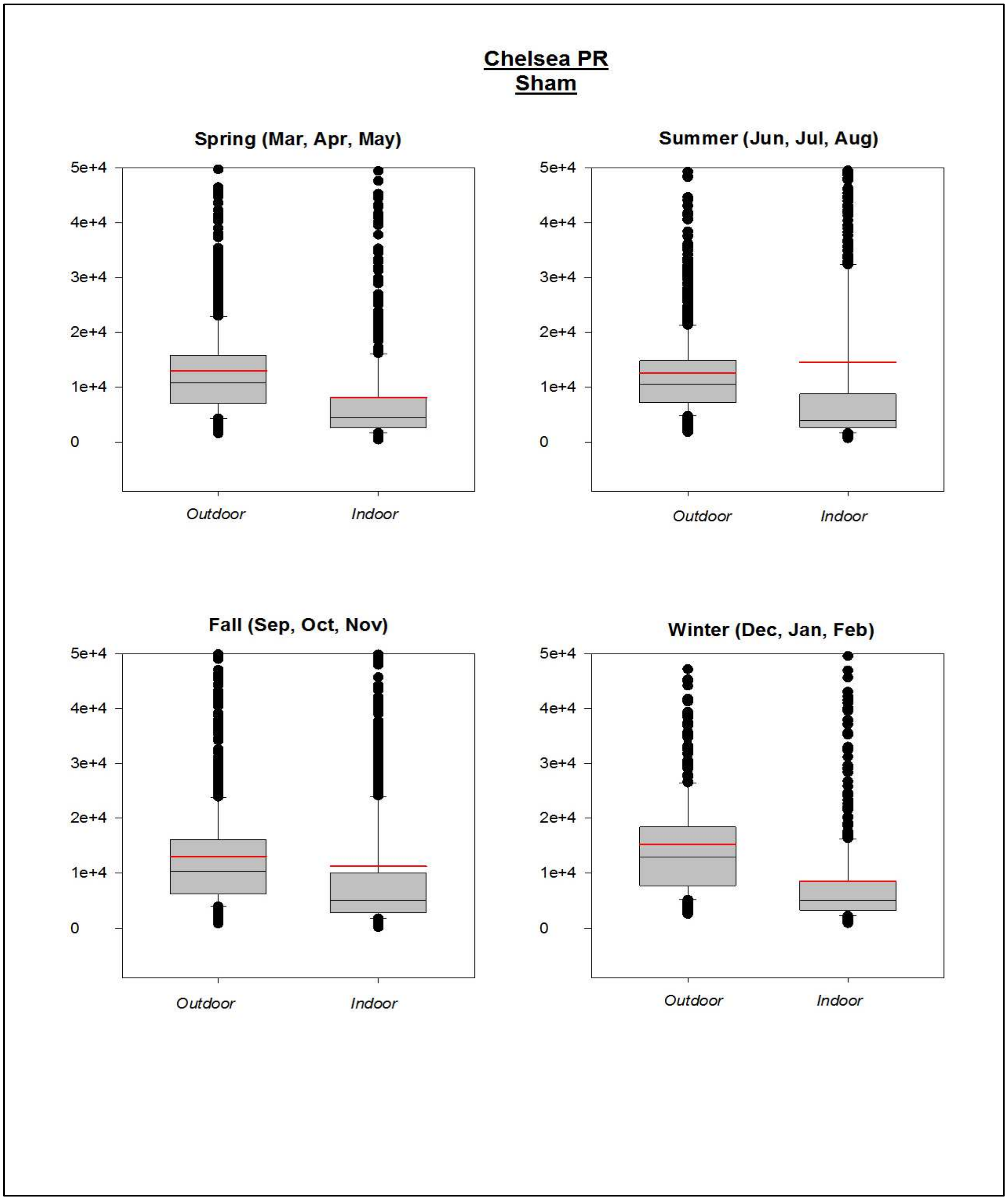


Figure 14. Boxplot of PNC measurements for all 10 Chelsea participants for each season

4.0. Discussion

This study described the temporal, monthly and seasonal, variation of PNC inside and outside of 24 homes in the Boston metropolitan area. Weekly variations of PNC for all 24 homes demonstrated the effect of various parameters on the weekly trends. High spikes in the indoor PNC variations were mostly related to indoor sources especially cooking as I compared the reported time of cooking to times of high spikes observed in the plots. The effects of outdoor sources were clearly observed in the low points in indoor air. These variations were committed to: 1. Understand the temporal pattern for all homes and how it matches our expectations from previous studies; 2. Understand the influence of cold and warm days on the median PNC during various months and seasons.

For the temporal weekly variations, it is likely that all indoor high-level PNC spikes are related to indoor activity and for most part cooking. Moreover, we understood that the instrument's malfunction and accuracy play an important role in the data's accuracy; therefore, affecting data processing on the next step. The indoor HEPA filtration weekly patterns illustrate a very low baseline for all participants compared to sham filtration weekly patterns. PR05, PR08, PR10 and PR13 didn't use any other extra AC than HEPA. Their results might be used to predict the effectiveness of HEPA filter during high spike particle number concentration. PR01, PR02, PR04, PR06, PR11 and PR20 have ACs in another room other than HEPA. PR02 uses the other AC while cooking, while PR06 uses it during night. This may be observed in weeks which we see lower spiked for

HEPA indoor measurements for PR02. Therefore, depending on the location of the other AC and the time which it was used, more knowledge could be extracted from the weekly variations. Moreover, PR12 uses a central air above HEPA unit, which this could have impacts on high spikes and low baselines during HEPA filtration.

From the seasonality analysis, we found that median indoors PNC is lower than outdoor median PNC during sham filter measurements for both Boston and Chelsea. From the monthly variations of PNC we found that even though we have different number of data for each month, the median for each month is not affected; however, the IQR is obviously more influenced.

From the reported daily activities, we found that the time of cooking is mostly related to high spikes; however, cleaning was also another indoor source reported in the field notebooks. The influence of electric stove or gas stove may not be observed in the weekly PNC patterns; however, the effect of use of another air conditioning (AC) may be observed in the weekly trend. The use of another AC and the number of extra ACs and the location of the AC, either far or close to HEPA filter may have an effect on the results (Table 7).

HEPA filter effect on air quality is determined by this design study. The use of two different filter scenarios, three weeks of HEPA filter measurement and sham filter measurement, provided good data on the efficiency of HEPA. The results in weekly variations, confirm that during low PNC values for all six weeks, the three weeks of HEPA have lower indoor PNC values compared to sham. The maximum PNC value was usually for indoor PNC during sham as expected.

Seasonally, during winter and fall for Boston homes, there is an increase in median PNC values (both indoors and outdoors); however, this might not be a characteristic of seasonality specifically due to different factors affecting the results. These factors include house type, individual's activities, and number of data points. Monthly variations illustrate the number of homes included in that specific month, having the most data collection during summer and the month of September and October. This, however, could be a reasonable validation for the data.

For most of the participants, the IQR during indoor sham measurements is slightly higher than indoor HEPA for Boston participants. To determine the efficiency of HEPA filter, this may be another factor to consider.

5.0 Conclusions and Recommendations

To investigate the weekly, monthly and seasonal variations of PNC, as well as to identify and qualitatively analyze the effectiveness of HEPA filtration over sham filtration, data collection was conducted during 2012 until 2014 at 24 homes in the Boston metropolitan area. Median PNC outdoor levels were constantly higher than those measured indoors at all 24 homes and phases of the study. Indoor PNC were comparable to their corresponding outdoor concentrations with an median indoor outdoor ratio less than 1.0 for all participants during sham filtration, indicating a strong impact of outdoors sources on the indoor particle number concentrations. Indoor baseline of PNC during sham filtration is suspected to be mostly affected by outdoor sources. By contrast, lower baseline is exhibited in the weekly variations during HEPA filtrations compared to sham filtration for all participants. Some participants exhibited low I/O for monthly variations compared to others, reflecting the impact of different factors including other ACs, open windows and instrument malfunction on the results.

HEPA filtration weekly variation results revealed that high spikes during indoor measurements were mostly dominated by indoor sources. Based on some reported indoor activities by the participants, cooking and cleaning were the dominant factor impacting high spikes; however, the length of the spikes, is suspected to be dependent on the use of other ACs and the location of them. Moreover, during the cold phase PNC measurements, there are higher median PNC levels during outdoor as well as indoor measurements. Both Boston and Chelsea present a high PNC level for colder seasons compared to warmer seasons in monthly and seasonally variation plots.

Our results suggest that even though each participant has different characteristics, there will be higher PNC during colder phases and that HEPA filters impact on air quality is significant. Therefore, a full understanding of the weekly, monthly and seasonal variations of PNC during HEPA and sham filtration requires a detailed knowledge of the human activity patterns for each home. Moreover, our results provide important information on seasonal, weekly and monthly variation of PNC which are direct results of various climate processes in an urban atmosphere that alter the number of particle concentration under different weather conditions.

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Appendix

In this section, all the weekly variations for 14 homes for Boston and 10 homes in Chelsea and their boxplots for comparison are illustrated.

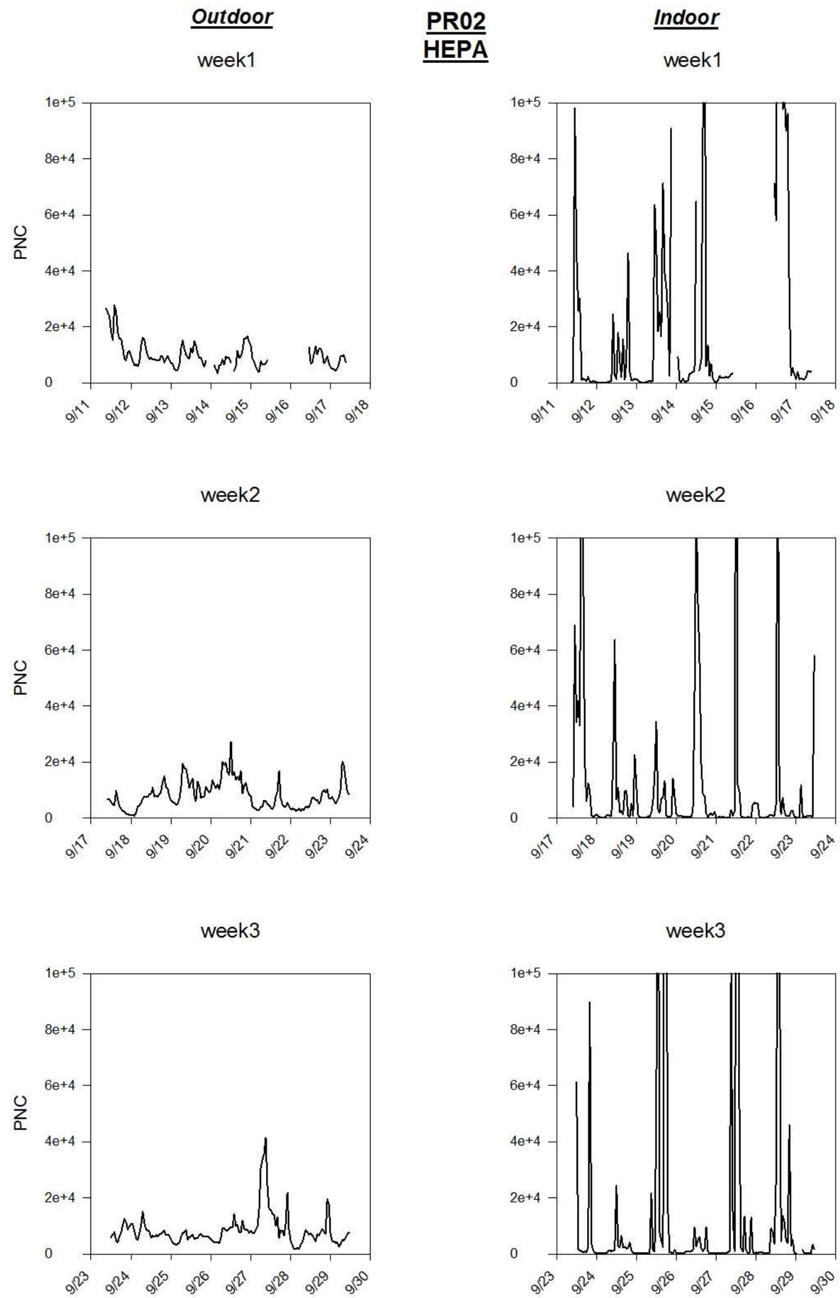


Figure 15. Weekly variations for PR02 during HEPA filtration

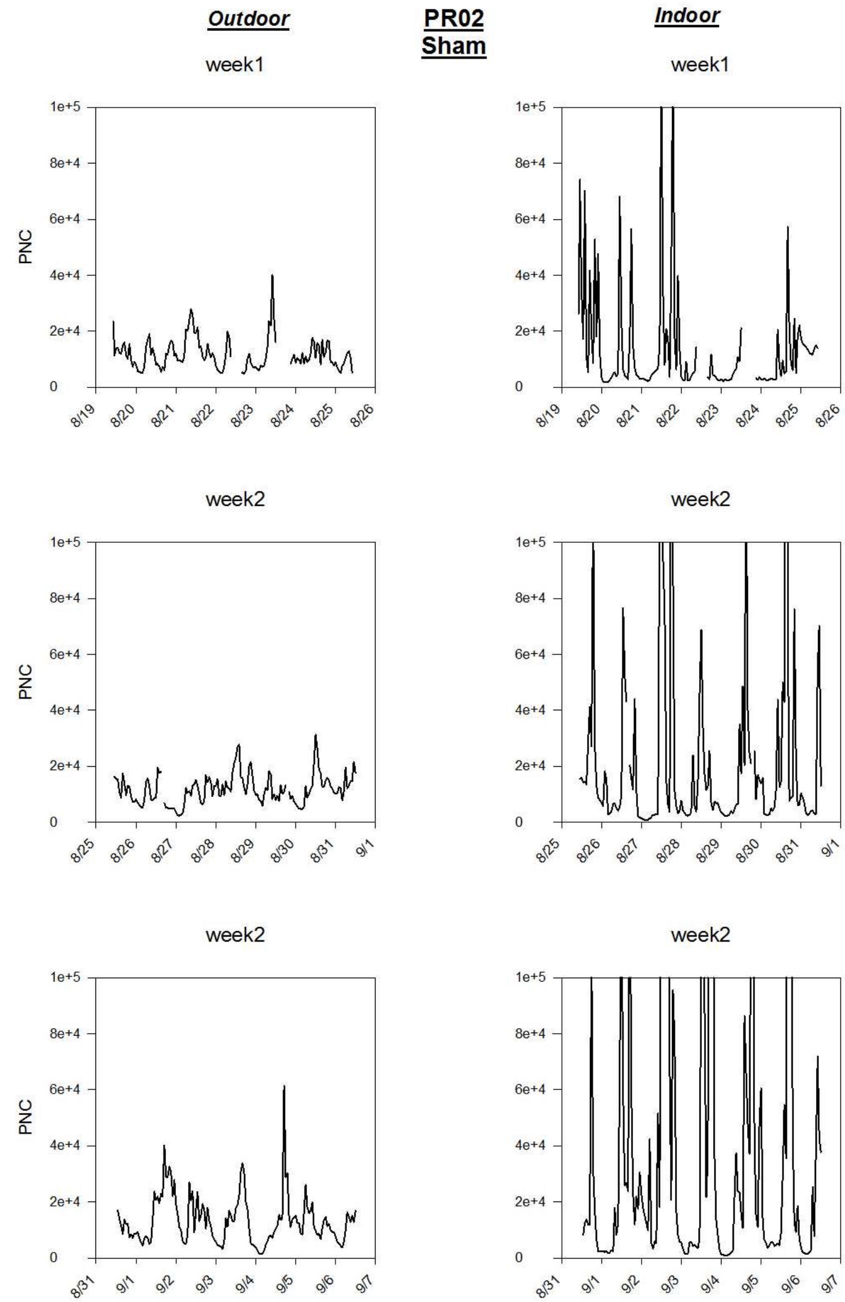


Figure 16. Weekly variations for PR02 during sham filtration

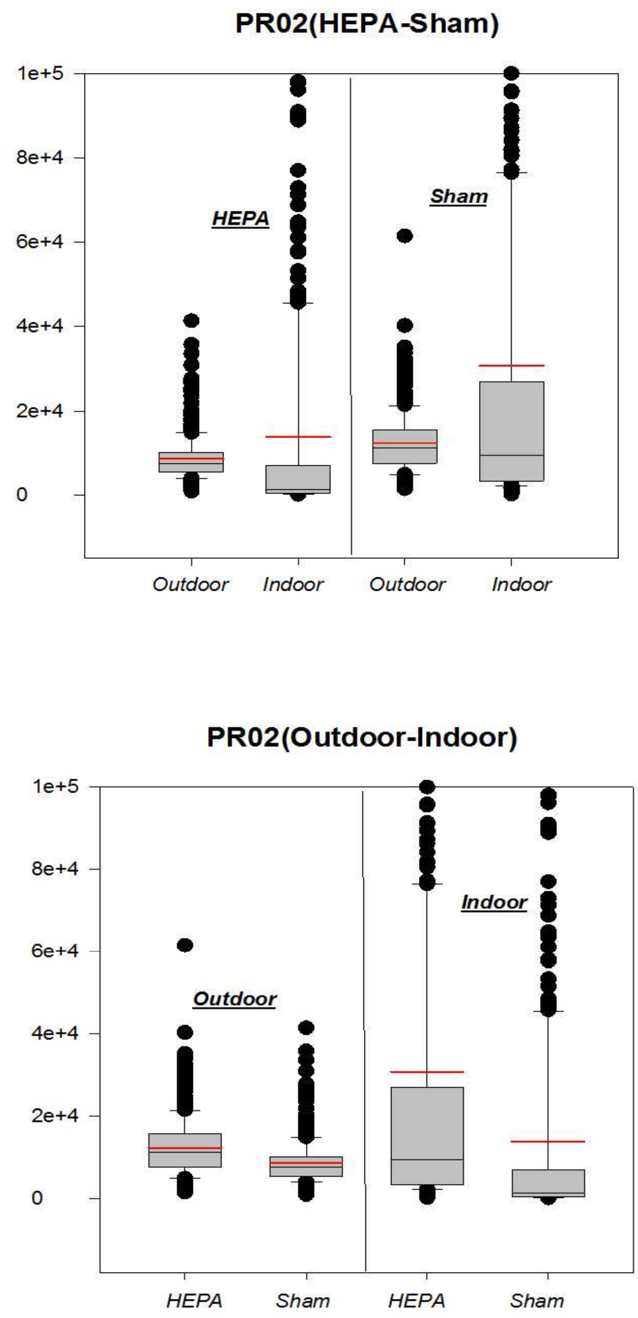


Figure 17. Boxplot for PR02 during HEPA and sham filtration

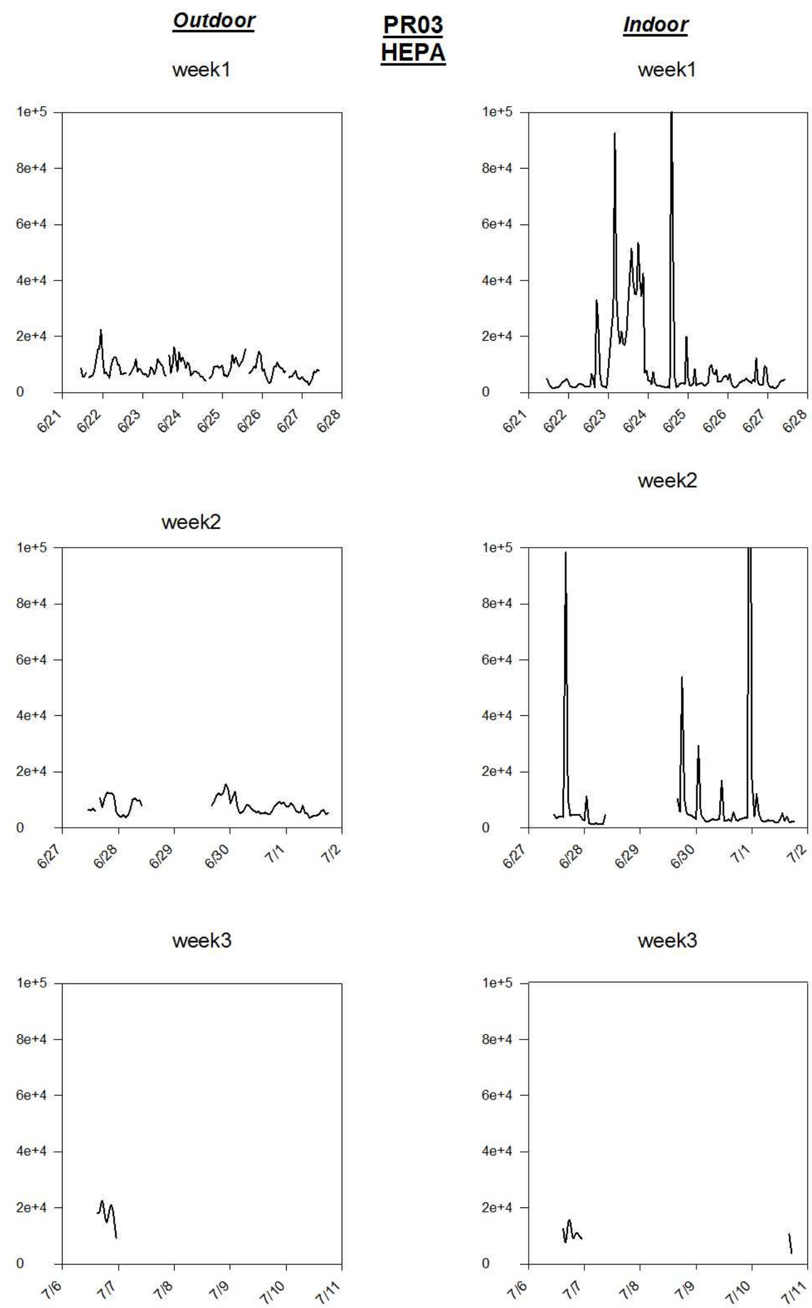


Figure 18. Weekly PNC variations for PR03 during HEPA filtration

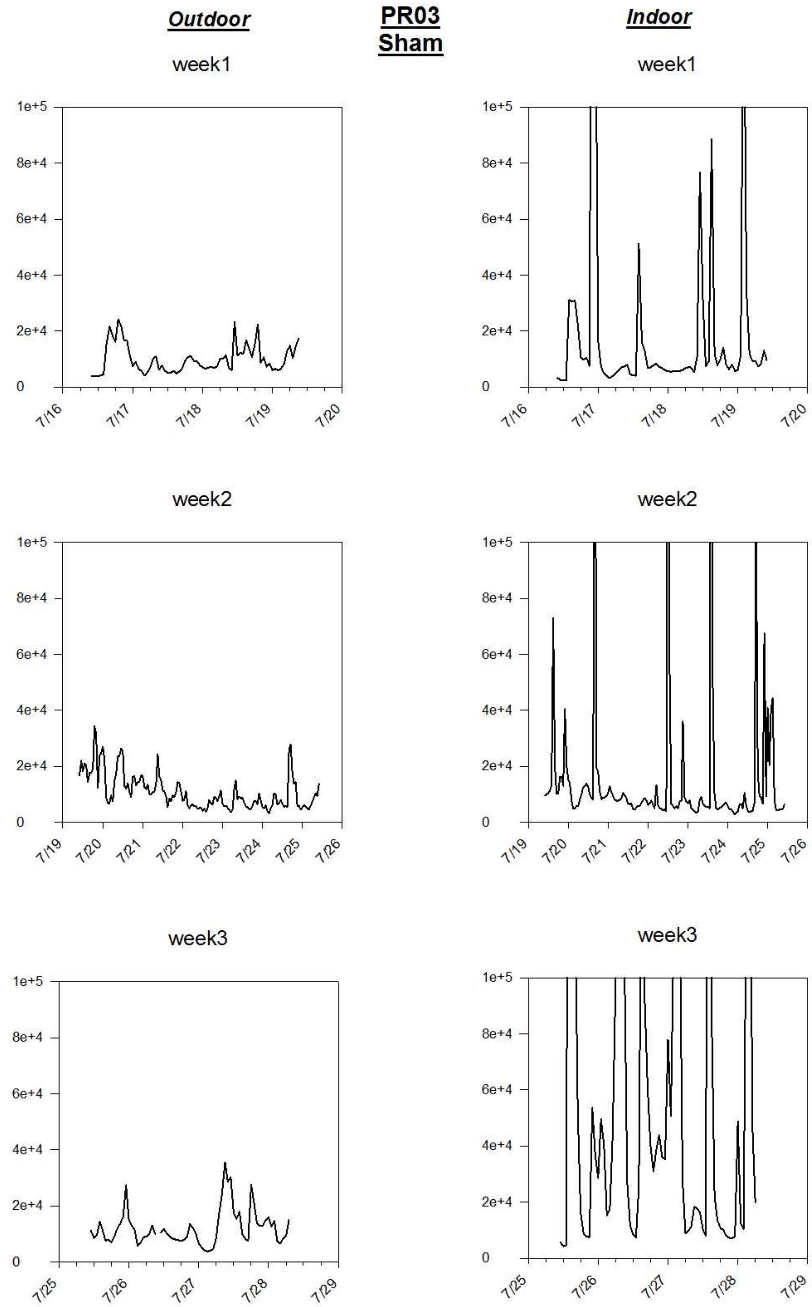
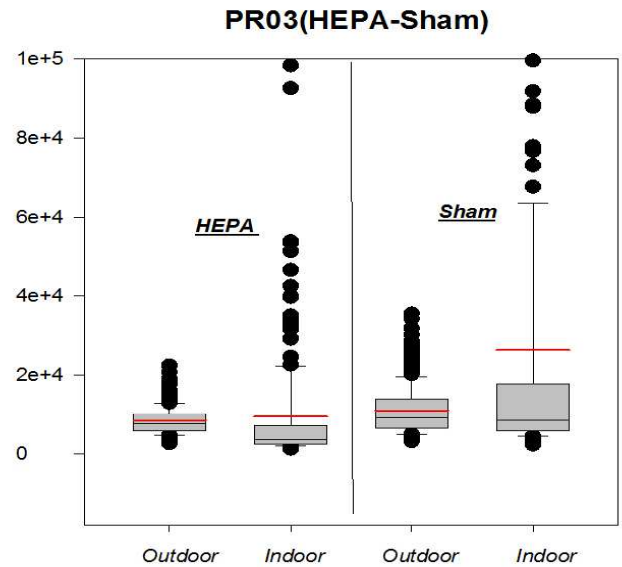


Figure 19. Weekly PNC variations for PR03 during sham filtration



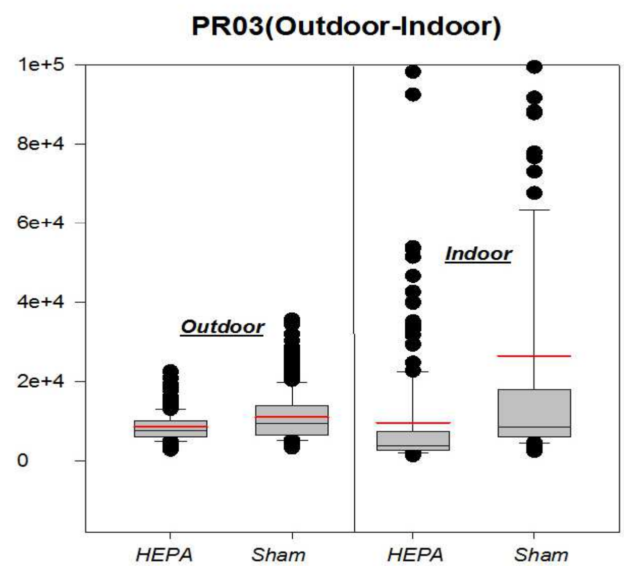


Figure 20. Boxplot for PNC variations for PR03 during HEPA and sham filtration

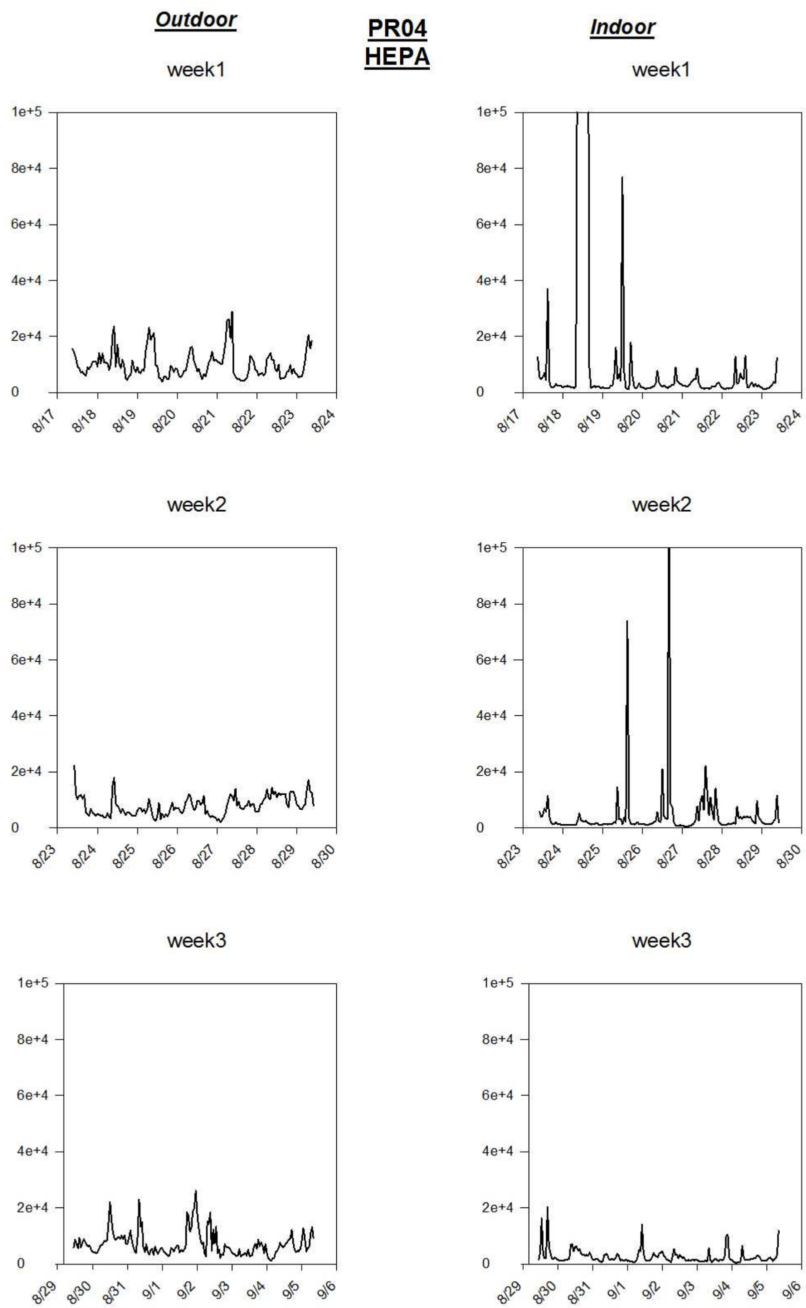


Figure 21. Weekly PNC variations for PR04 during HEPA filtration

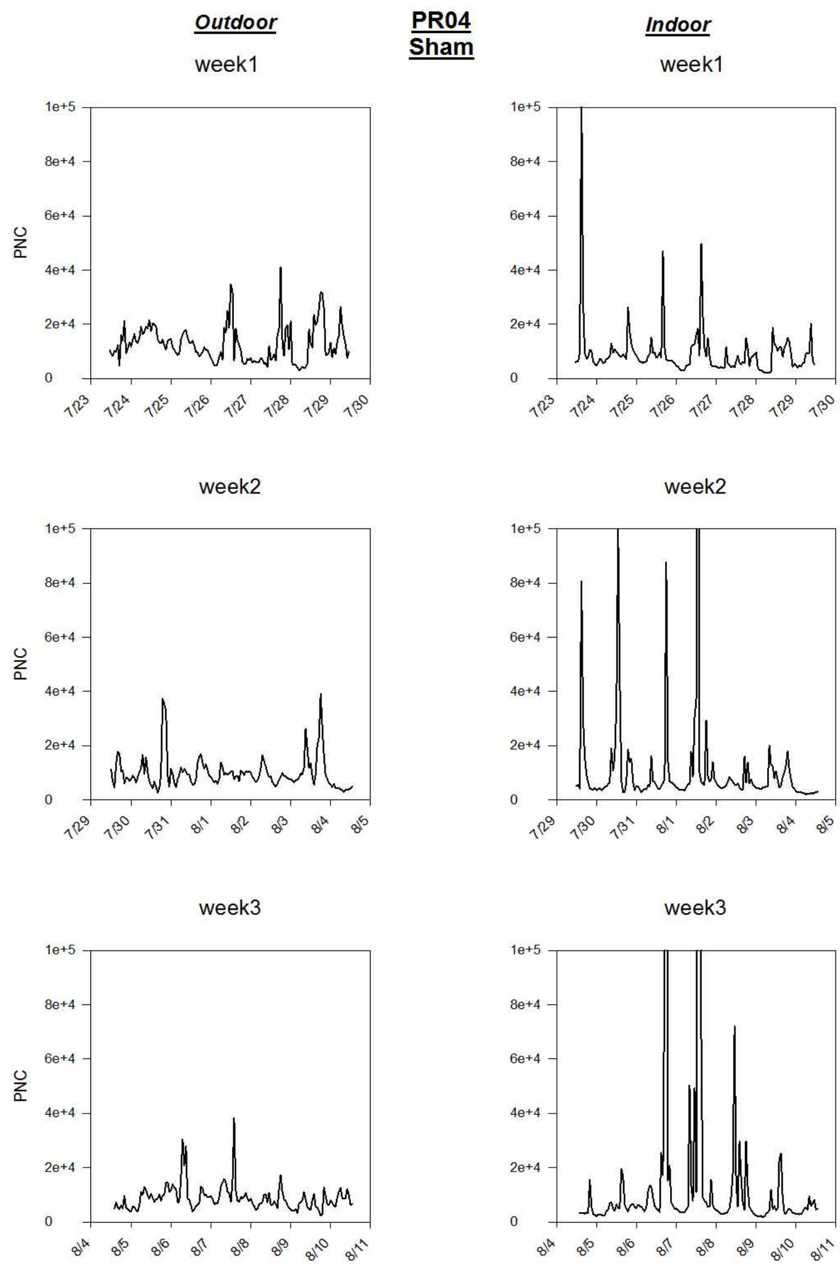
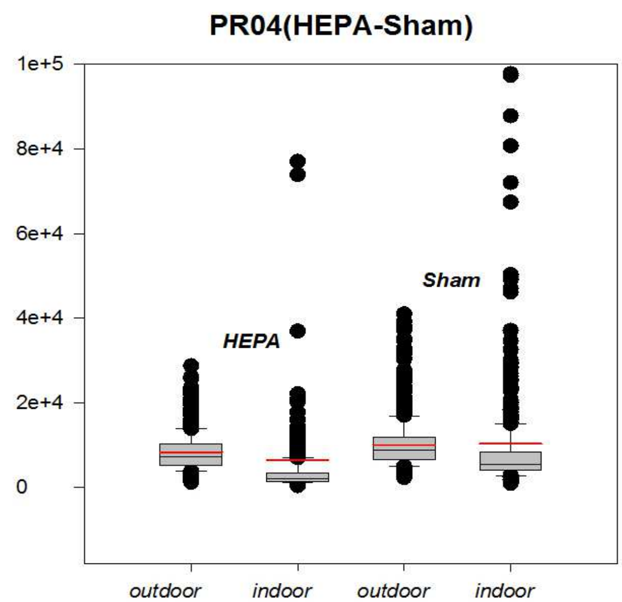


Figure 22. Weekly PNC variations for PR04 during sham filtration



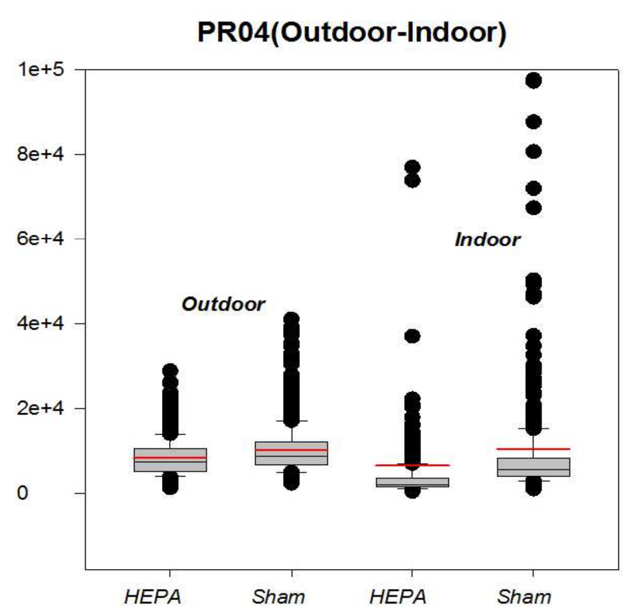


Figure 23. Boxplot for PNC variations for PR04

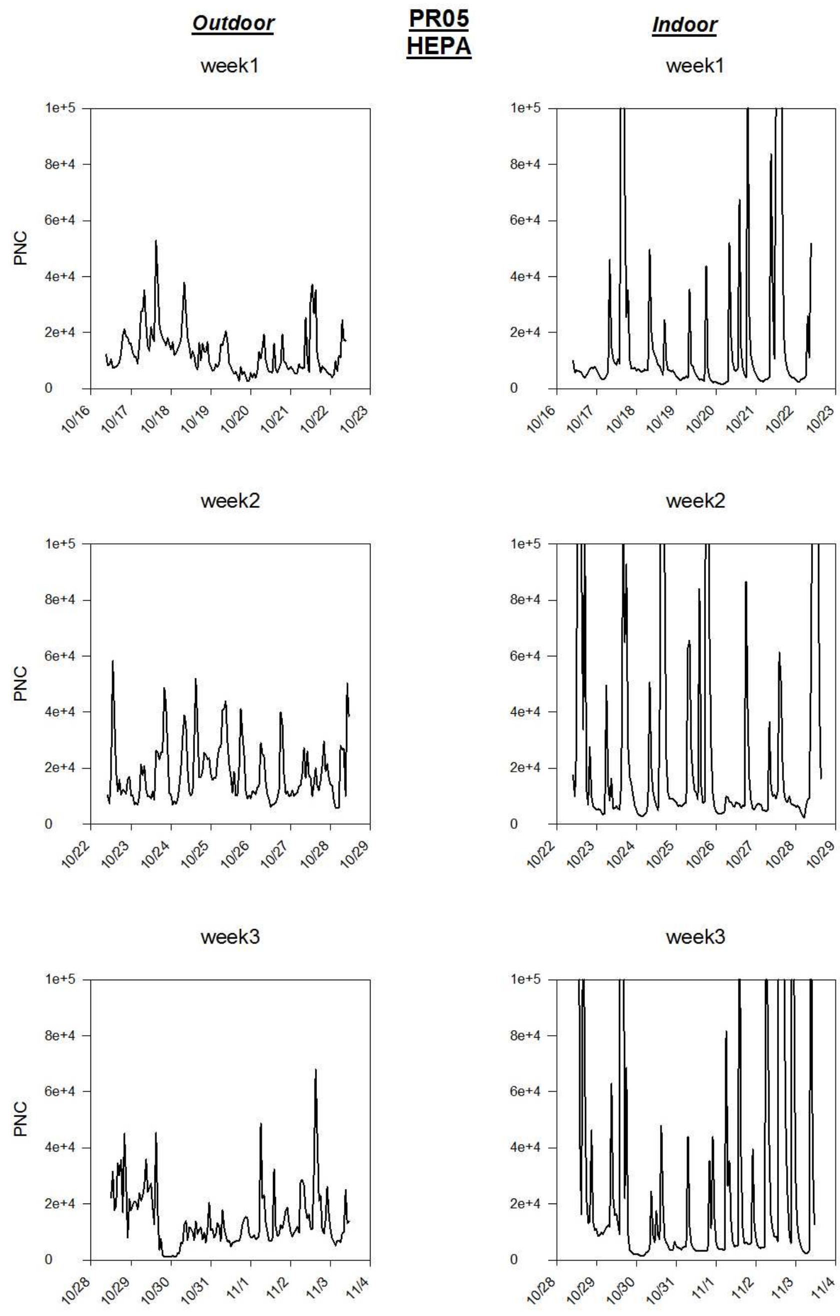


Figure 24. Weekly PNC variations for PR05 during HEPA filtration

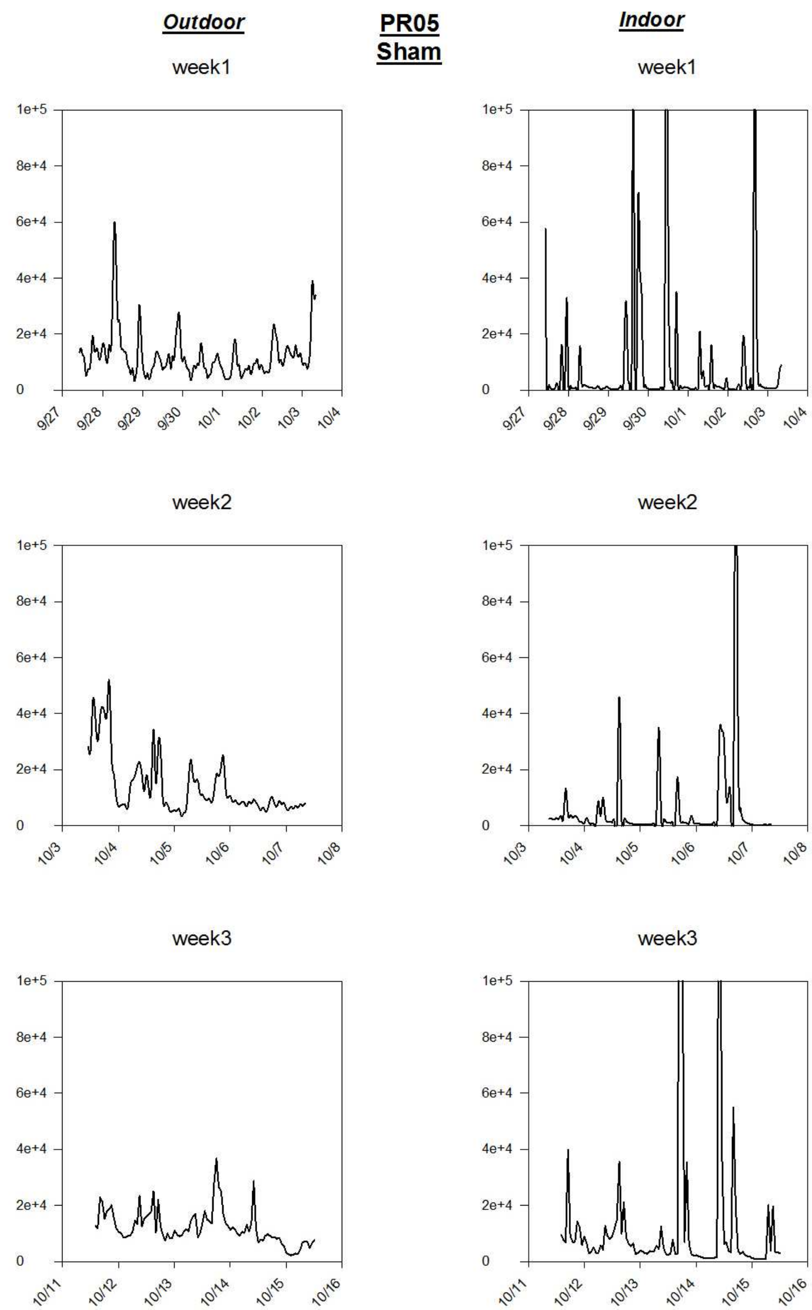
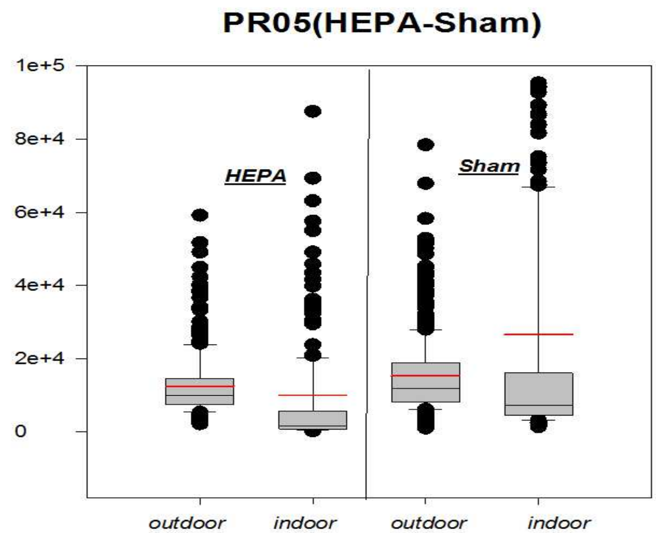


Figure 25. Weekly PNC variations for PR05 during sham filtration



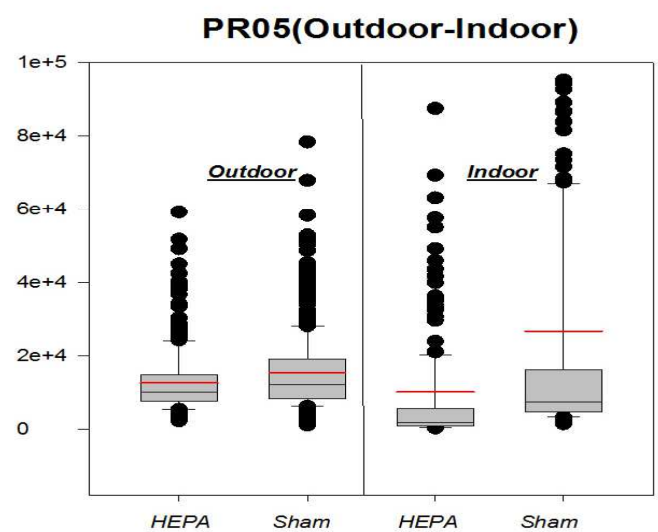


Figure 26. Boxplot for PNC variations for PR05

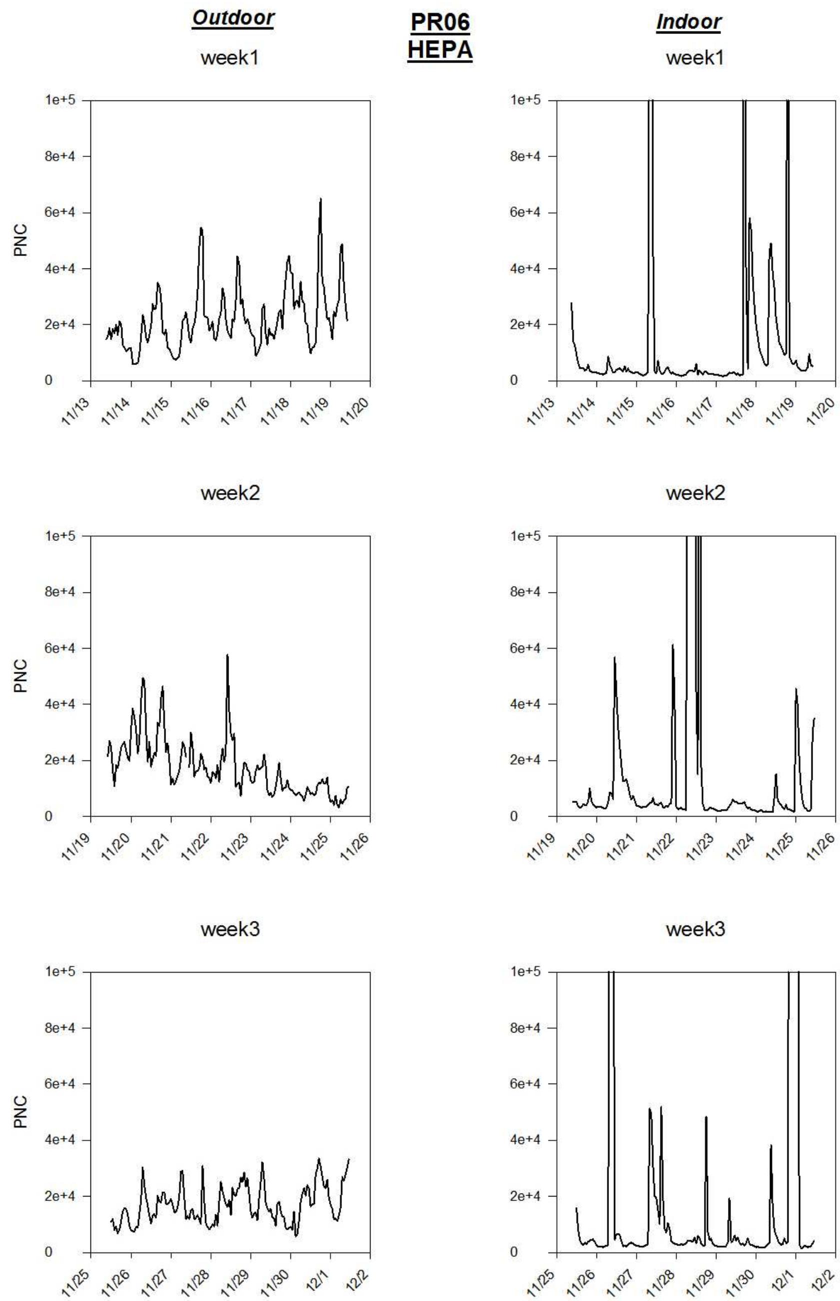


Figure 27. Weekly PNC variations for PR06 during HEPA filtration

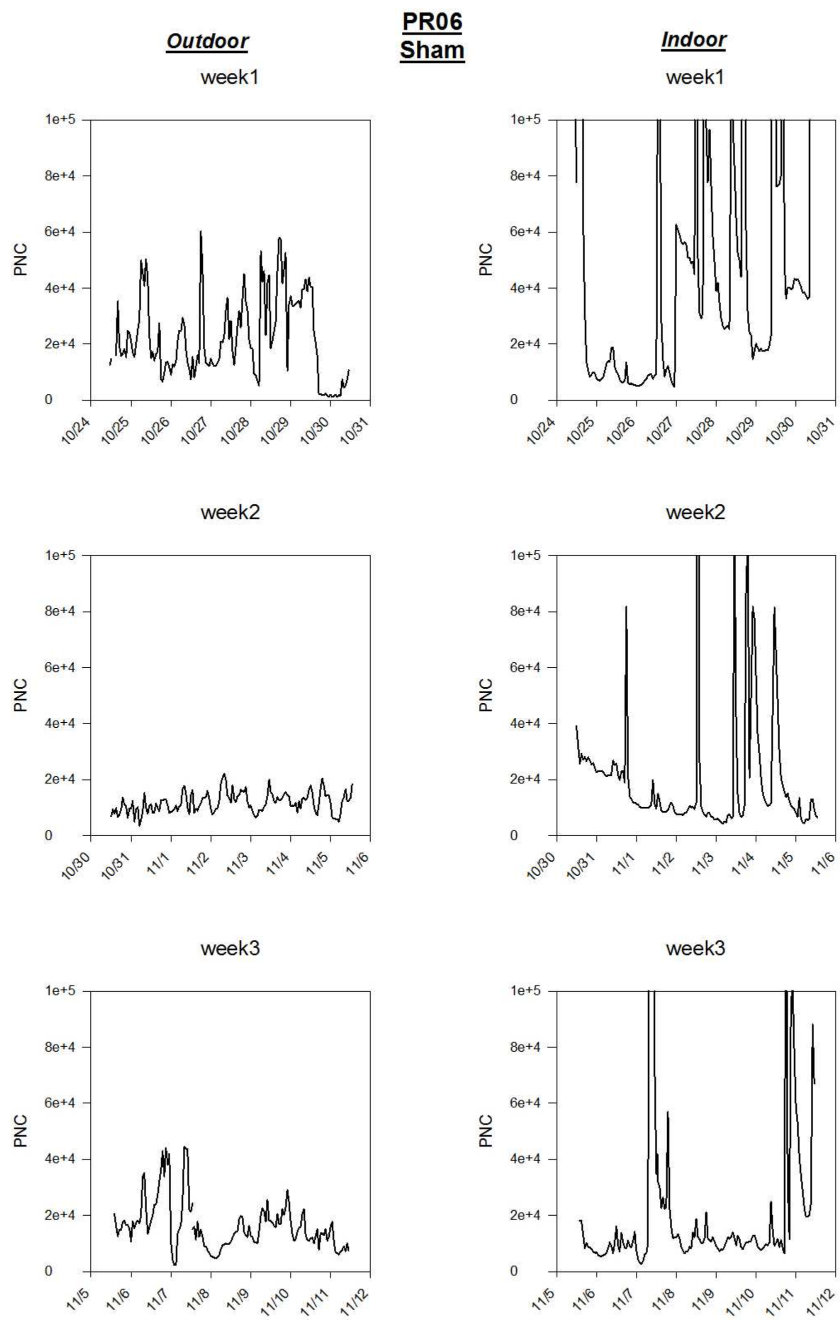


Figure 28. Weekly PNC variations for PR06 during sham filtration

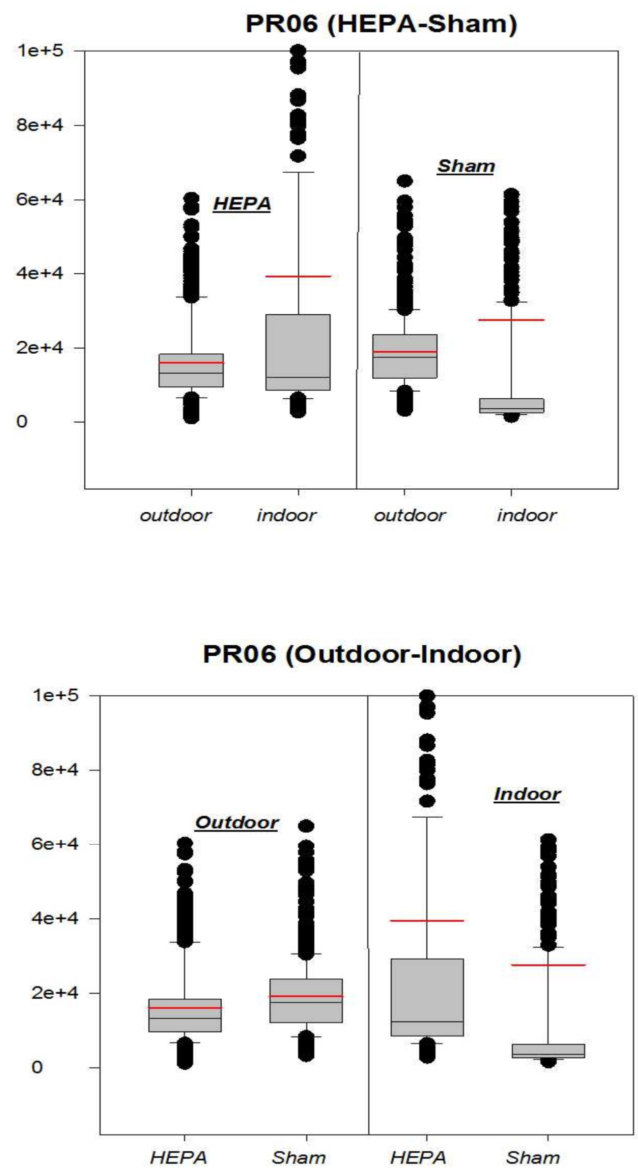


Figure 29. Boxplot for PNC variations during HEPA and sham filtration

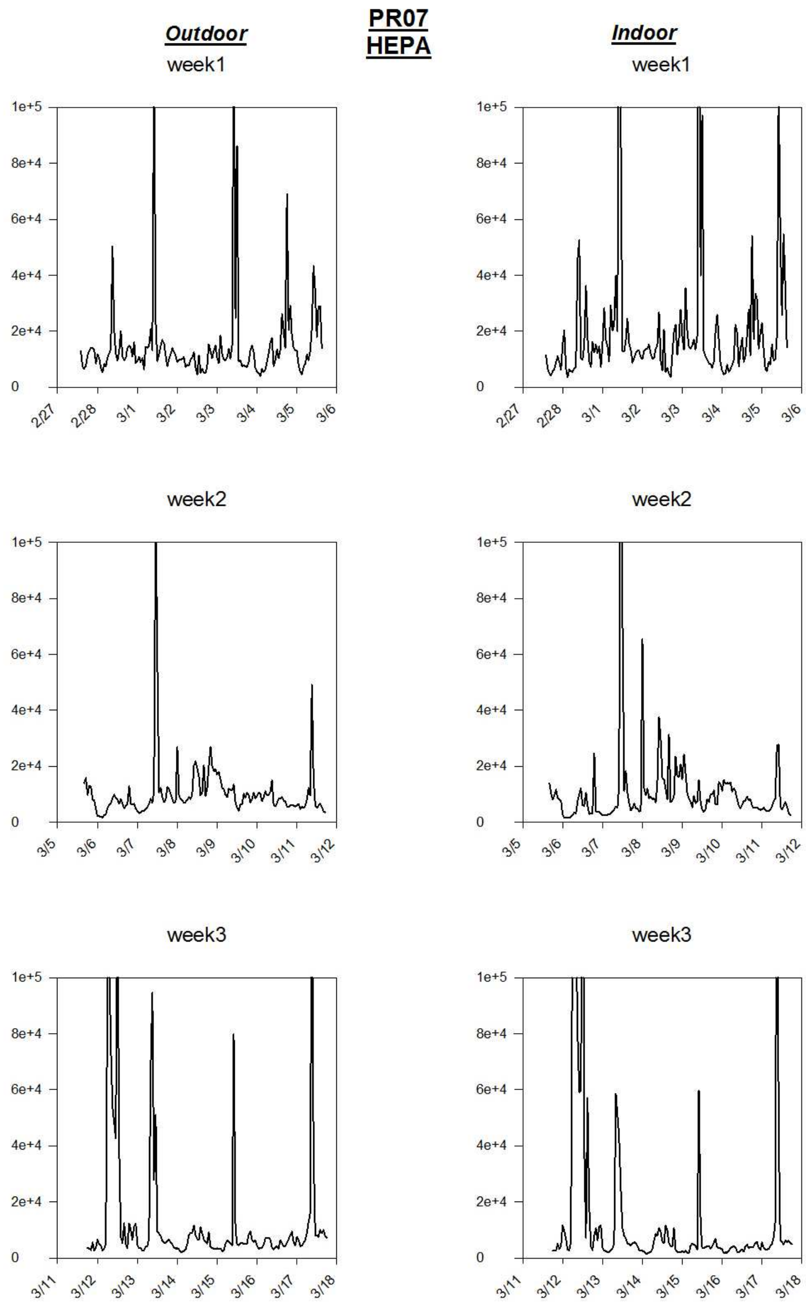


Figure 30. Weekly PNC variations for PR07 during HEPA filtration

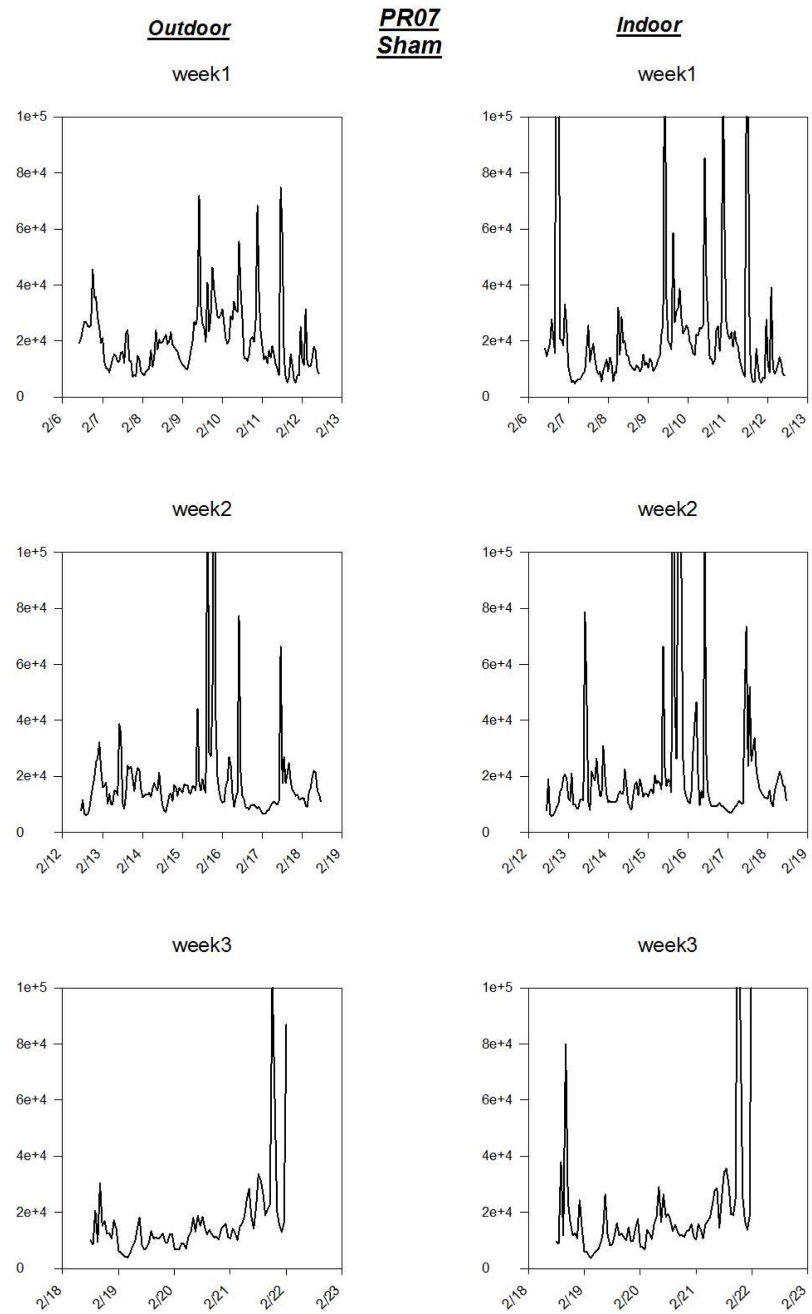


Figure 31. Weekly PNC variations for PR07 during sham filtration

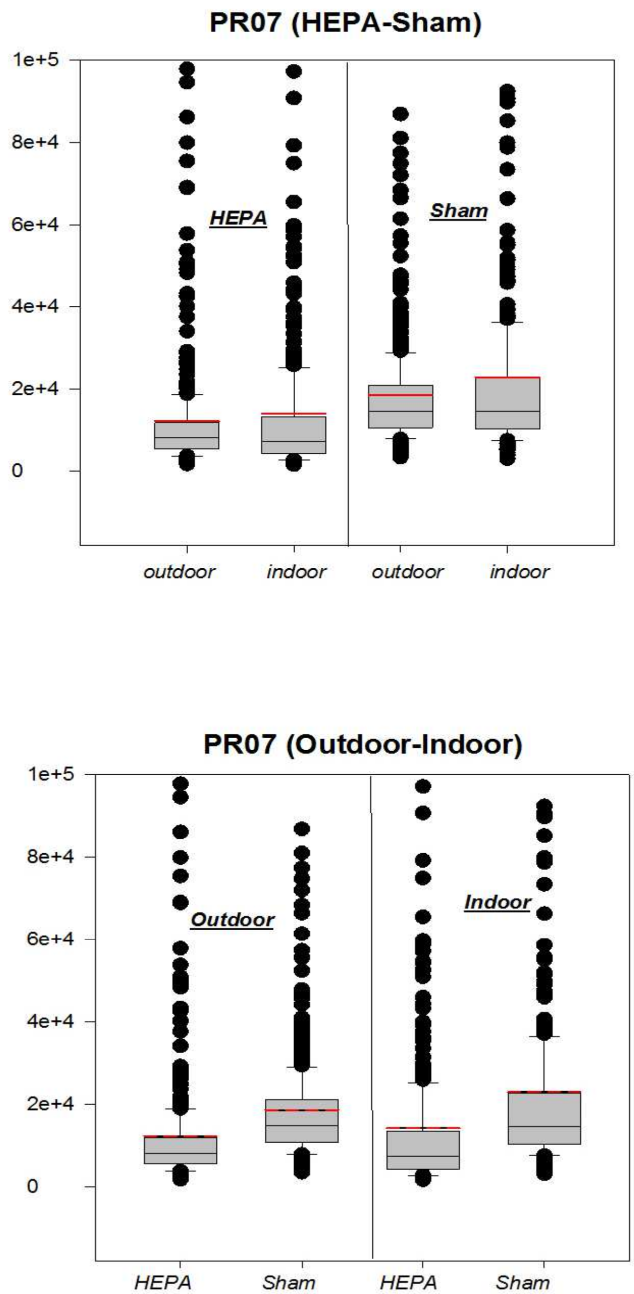


Figure 32. Boxplot for PNC variations for PR07 during HEPA and sham filtration

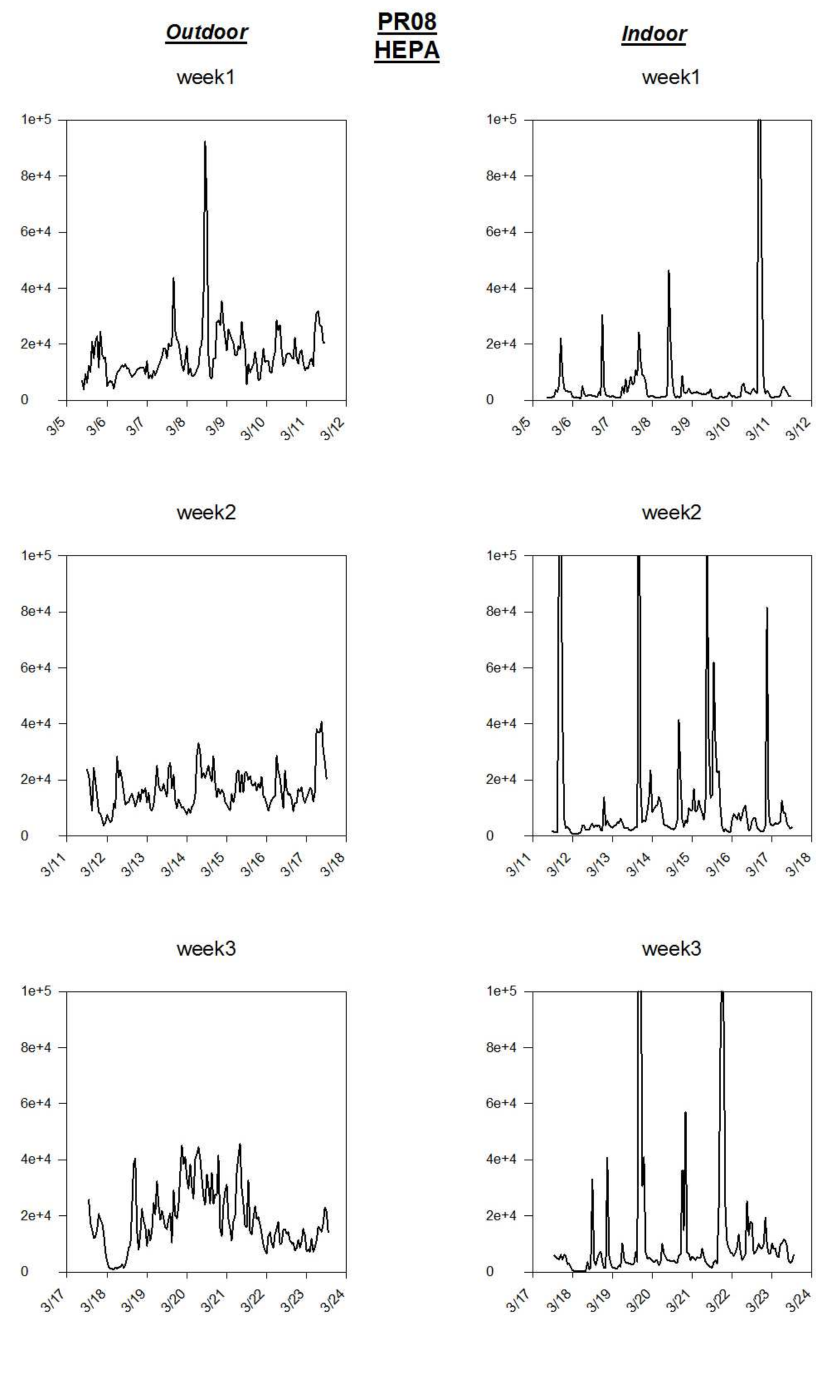


Figure 33. Weekly PNC variations for PR08 during HEPA filtration

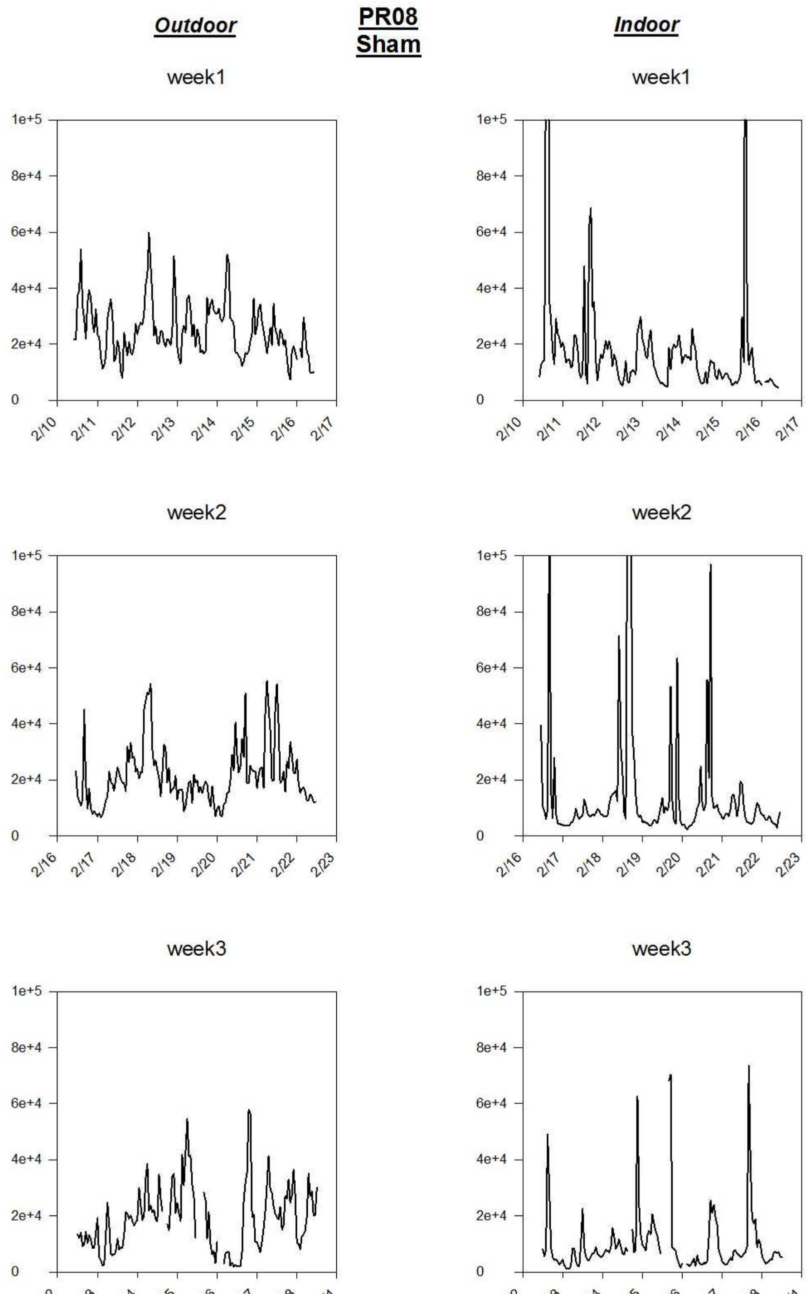
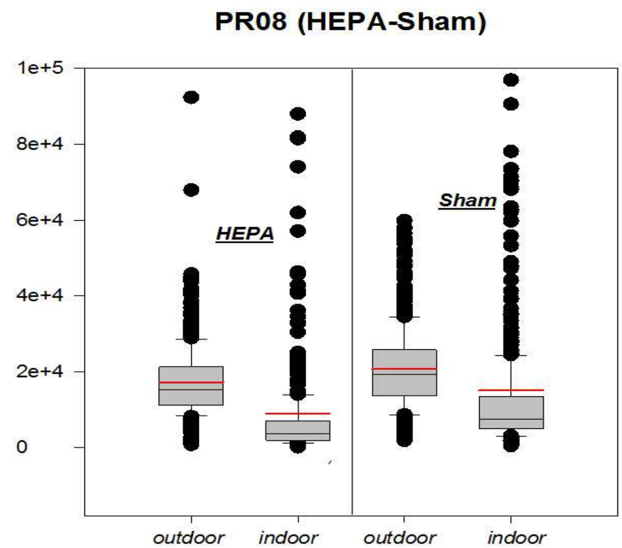


Figure 34. Weekly PNC variations for PR08 during sham filtration



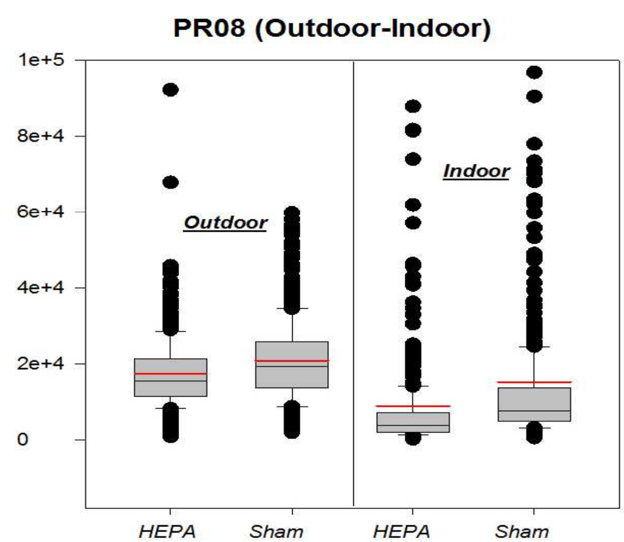


Figure 35. Boxplot for PNC variations for PR08 during HEPA and sham filtration

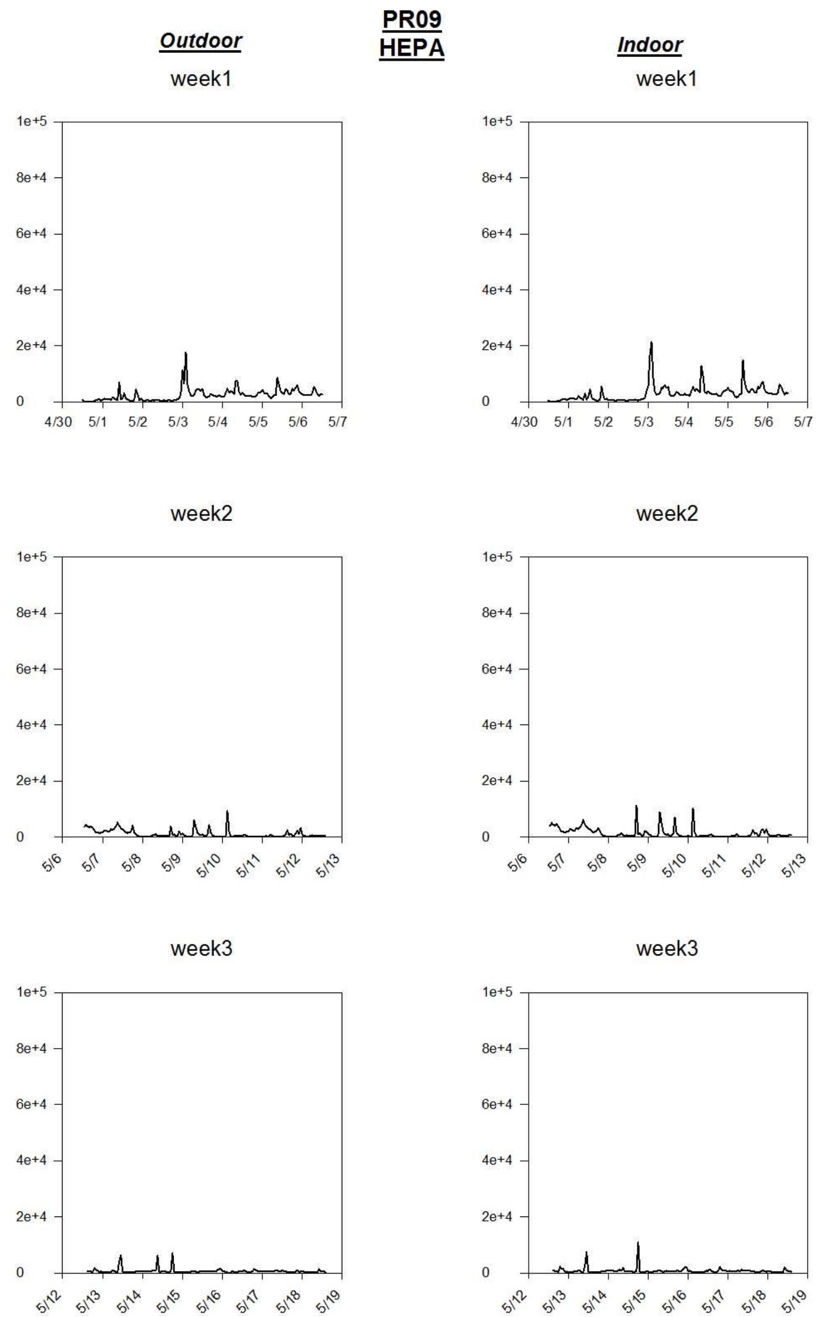


Figure 36. Weekly PNC variations for PR09 during HEPA filtration

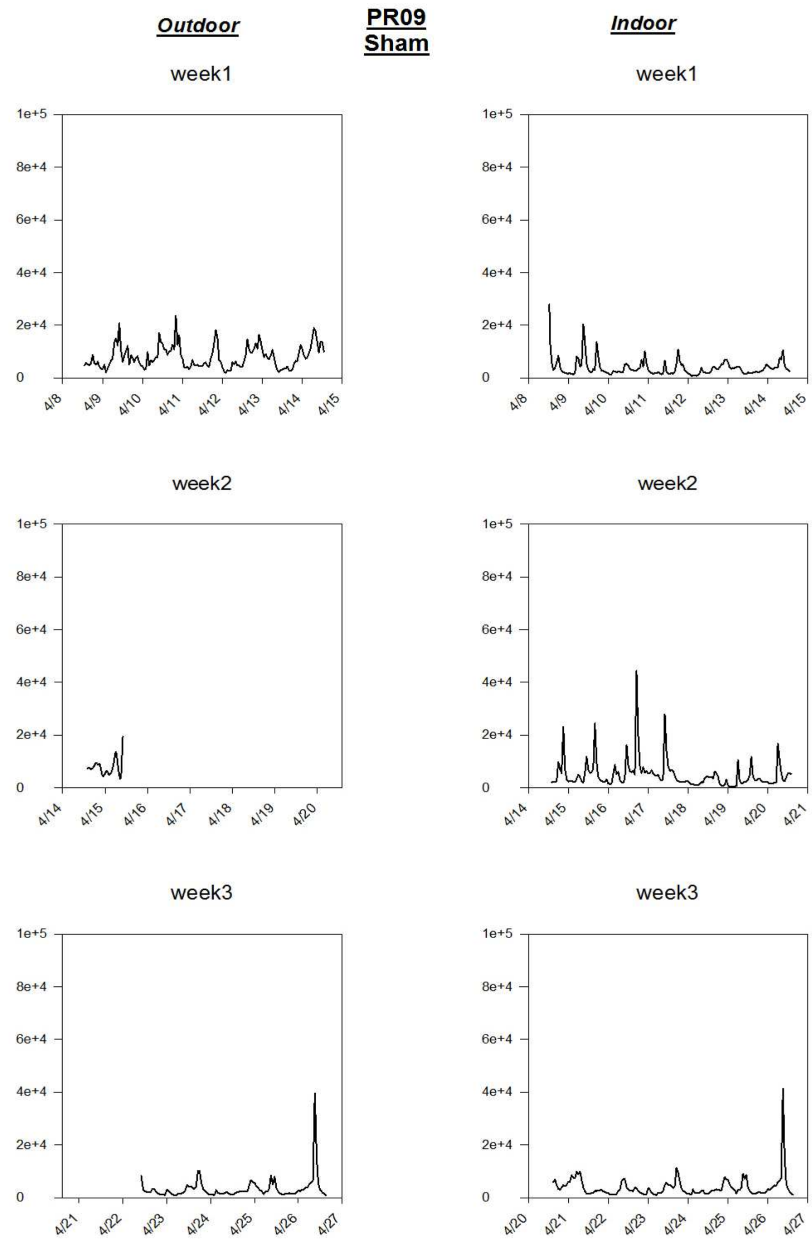


Figure 37. Weekly PNC variations for PR09 during sham filtration

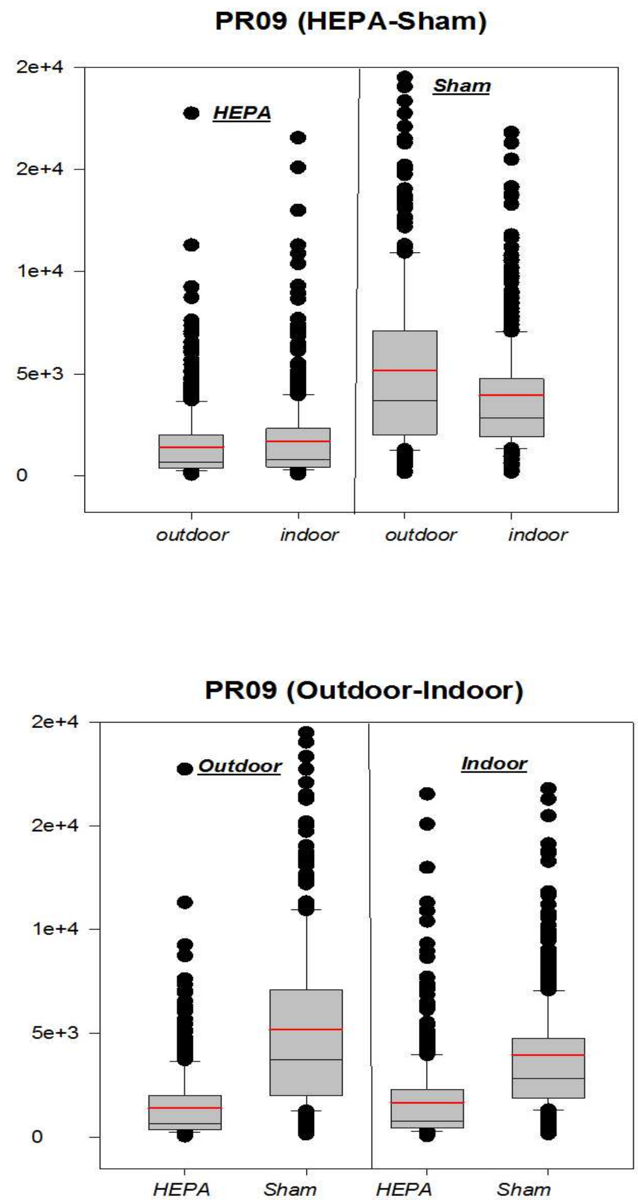


Figure 38. Boxplot for PNC variations for PR09 during HEPA and sham filtration

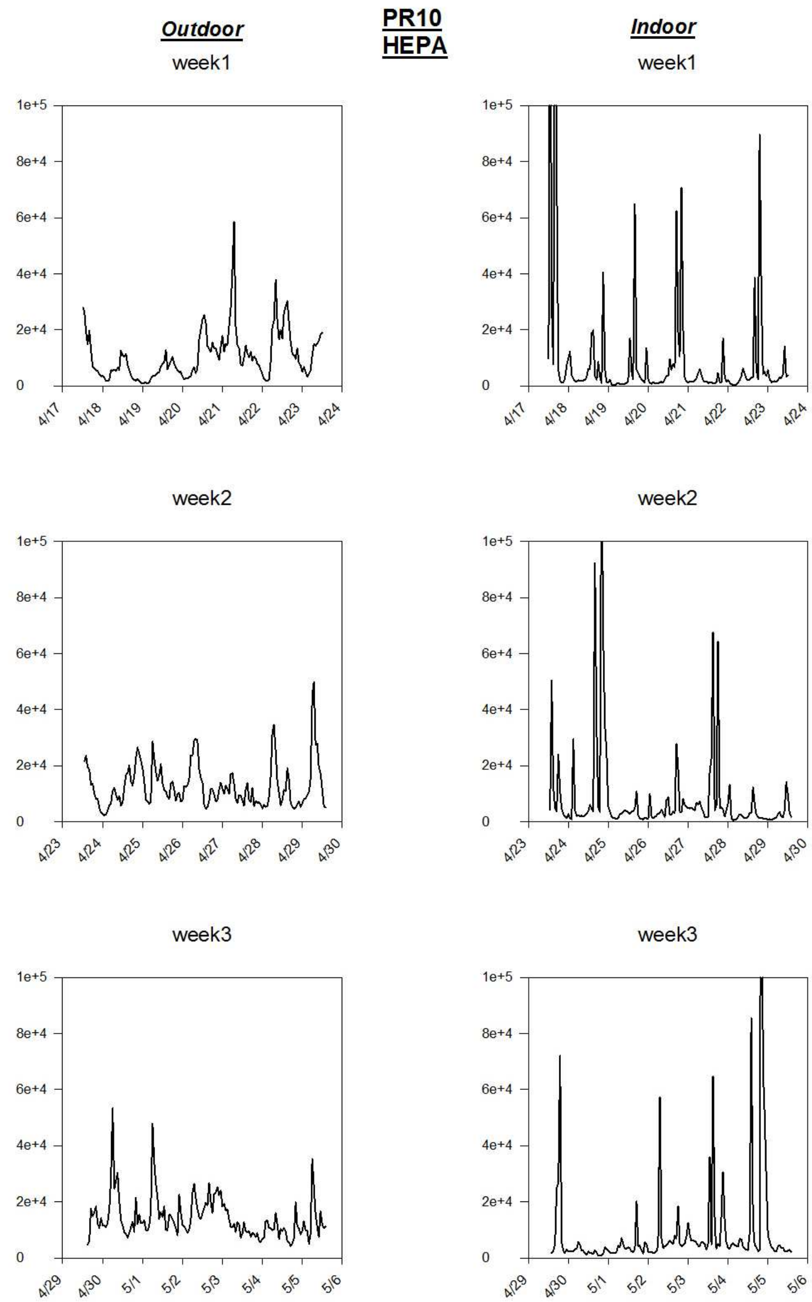


Figure 39. Weekly PNC variations for PR10 during HEPA and sham filtration

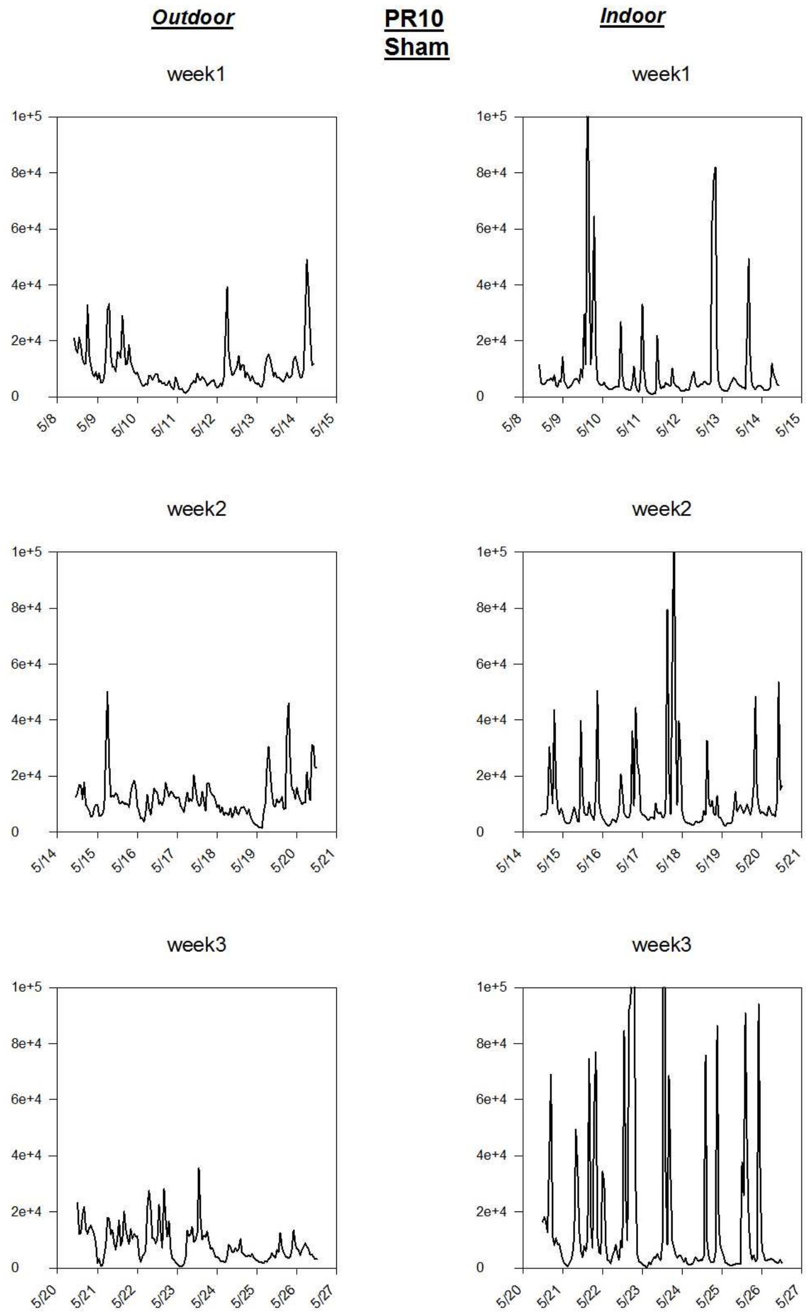


Figure 40. Weekly PNC variations for PR10 during sham filtration

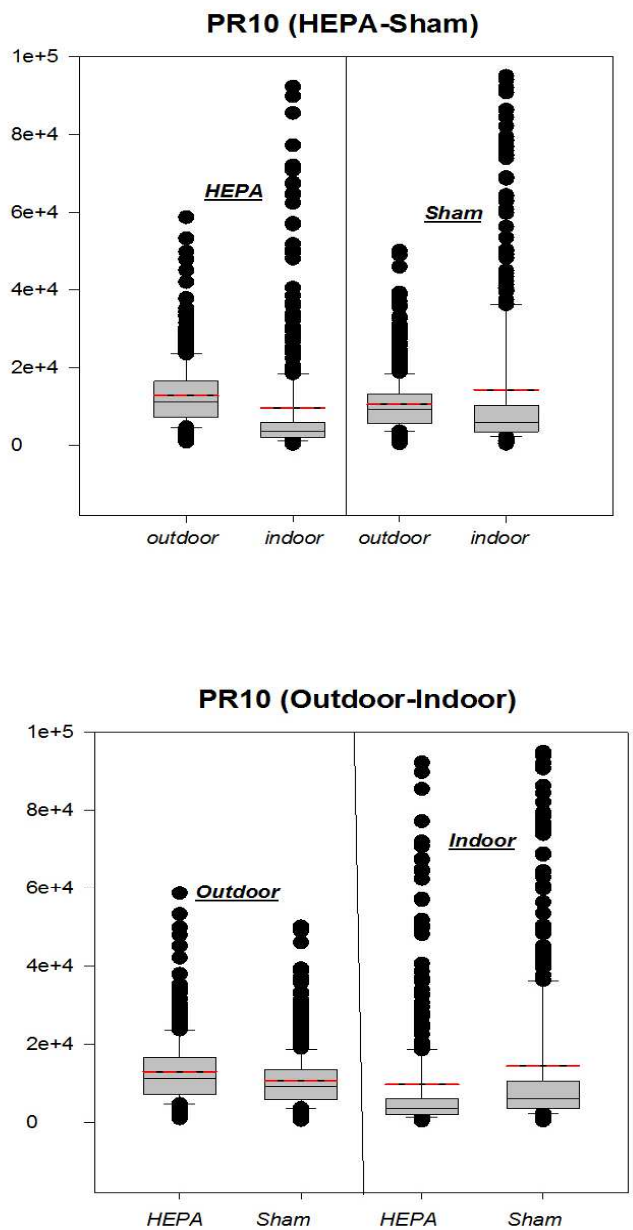


Figure 41. Boxplot for PNC variations for PR10 during HEPA and sham filtration

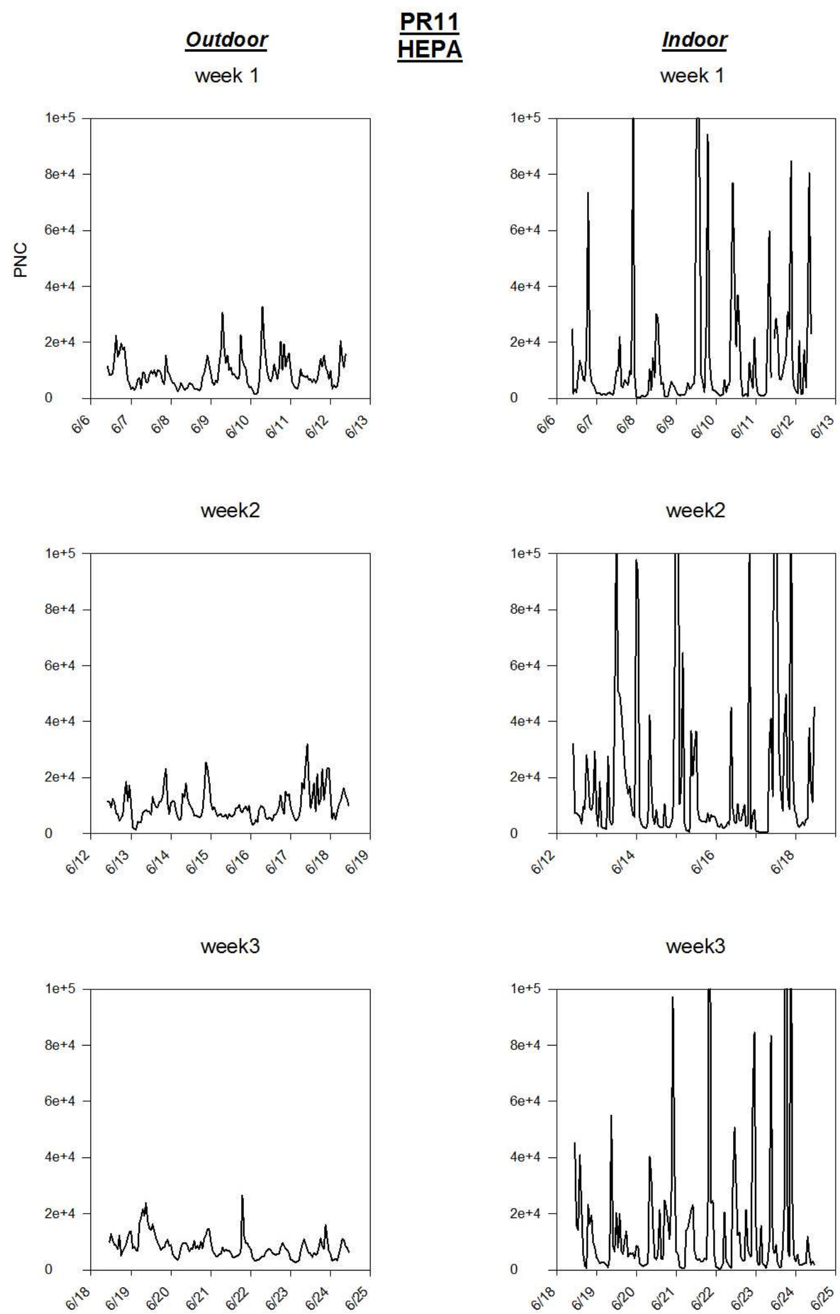


Figure 42. Weekly PNC variations for PR11 during HEPA filtration

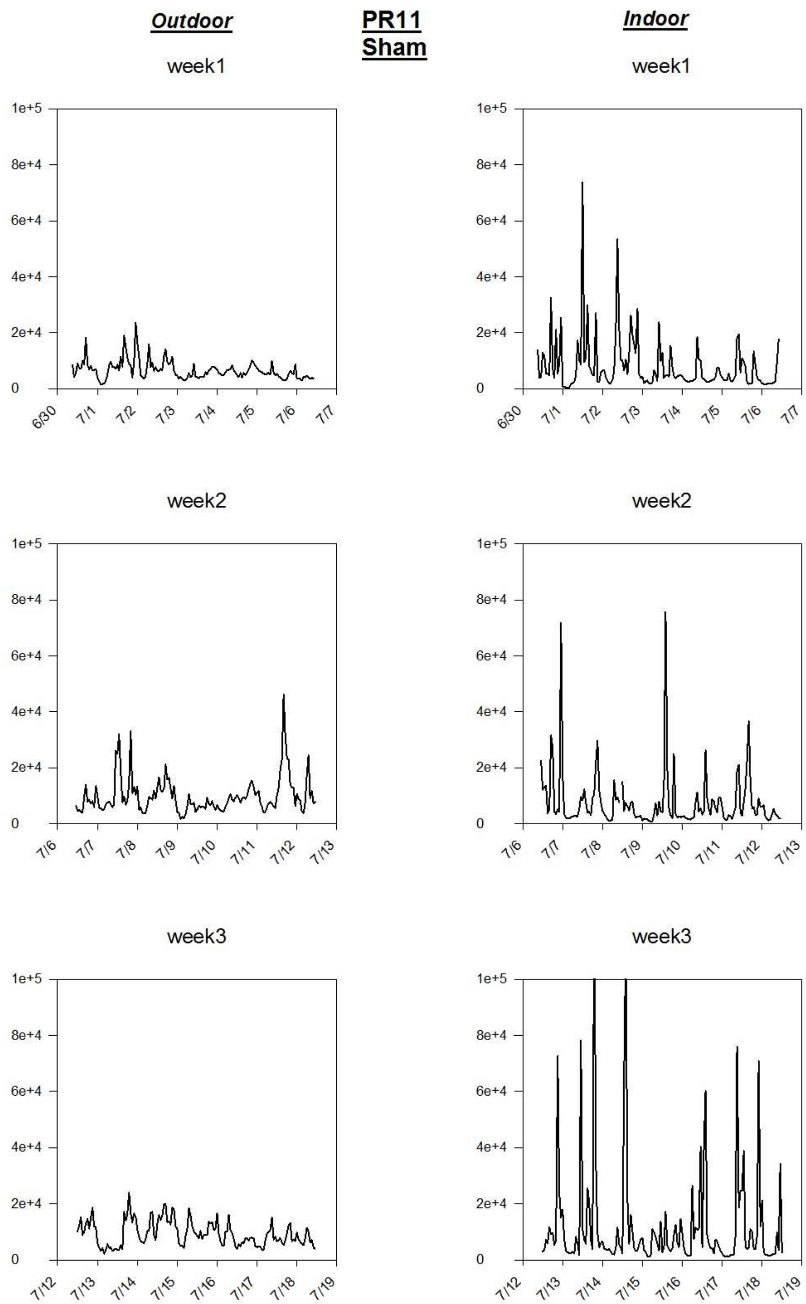
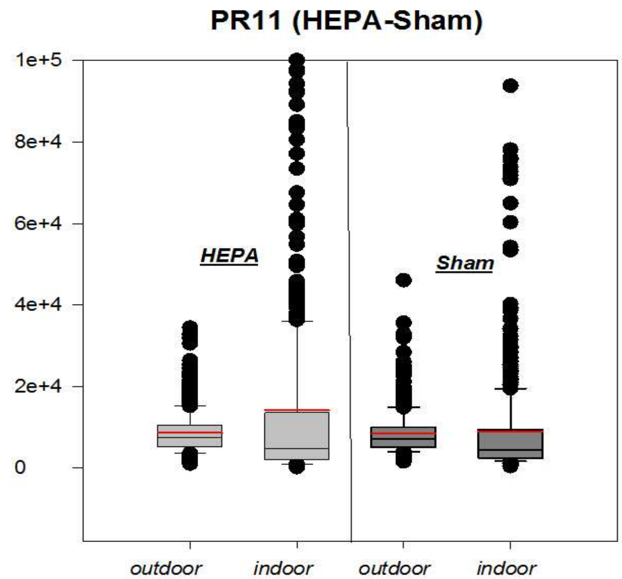


Figure 43. Weekly PNC variations for PR11 during sham filtration



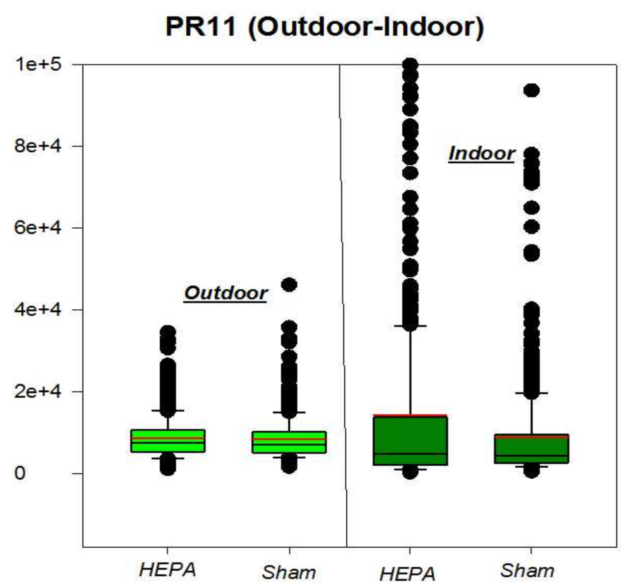


Figure 44. Boxplot for PNC variations for PR11 during HEPA and sham filtration

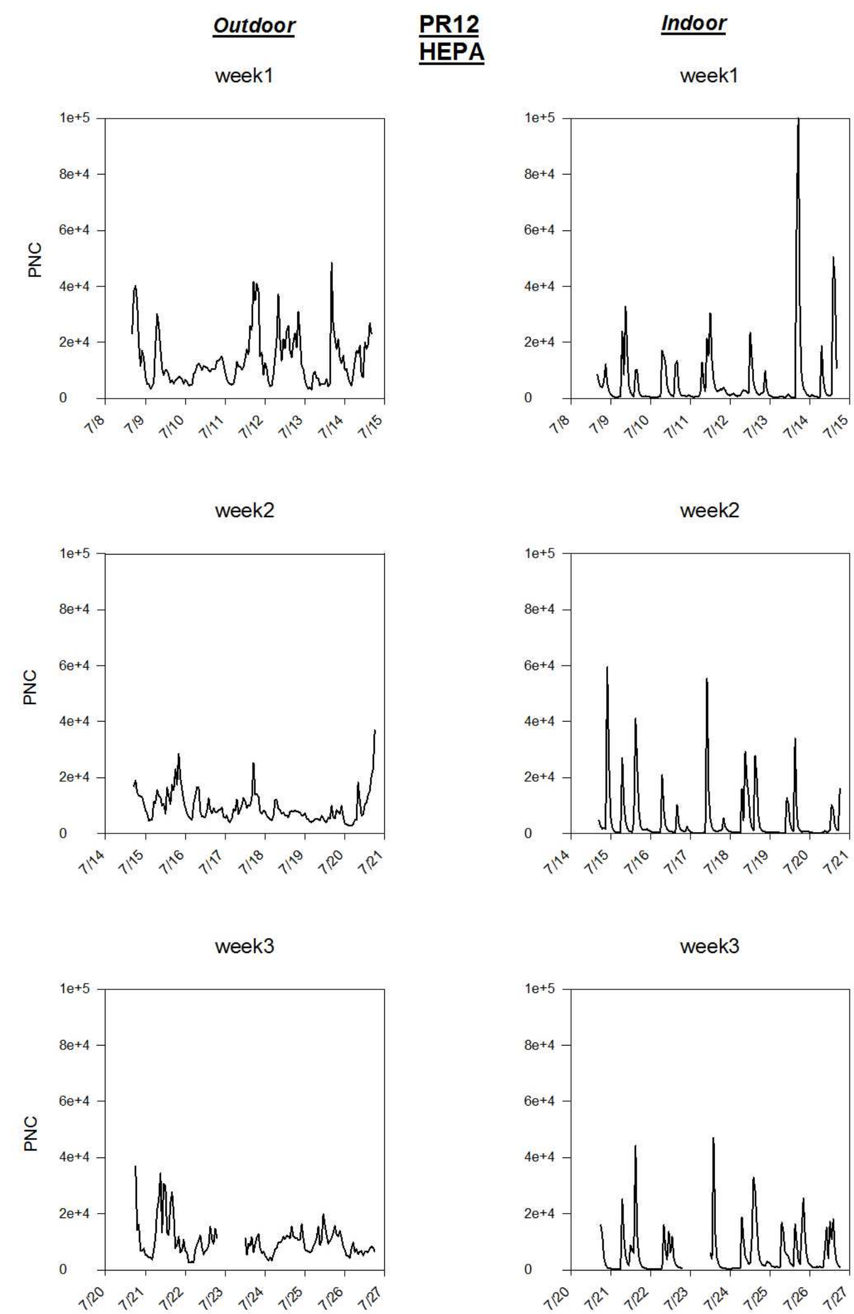


Figure 45. Weekly PNC variations for PR12 during HEPA filtration

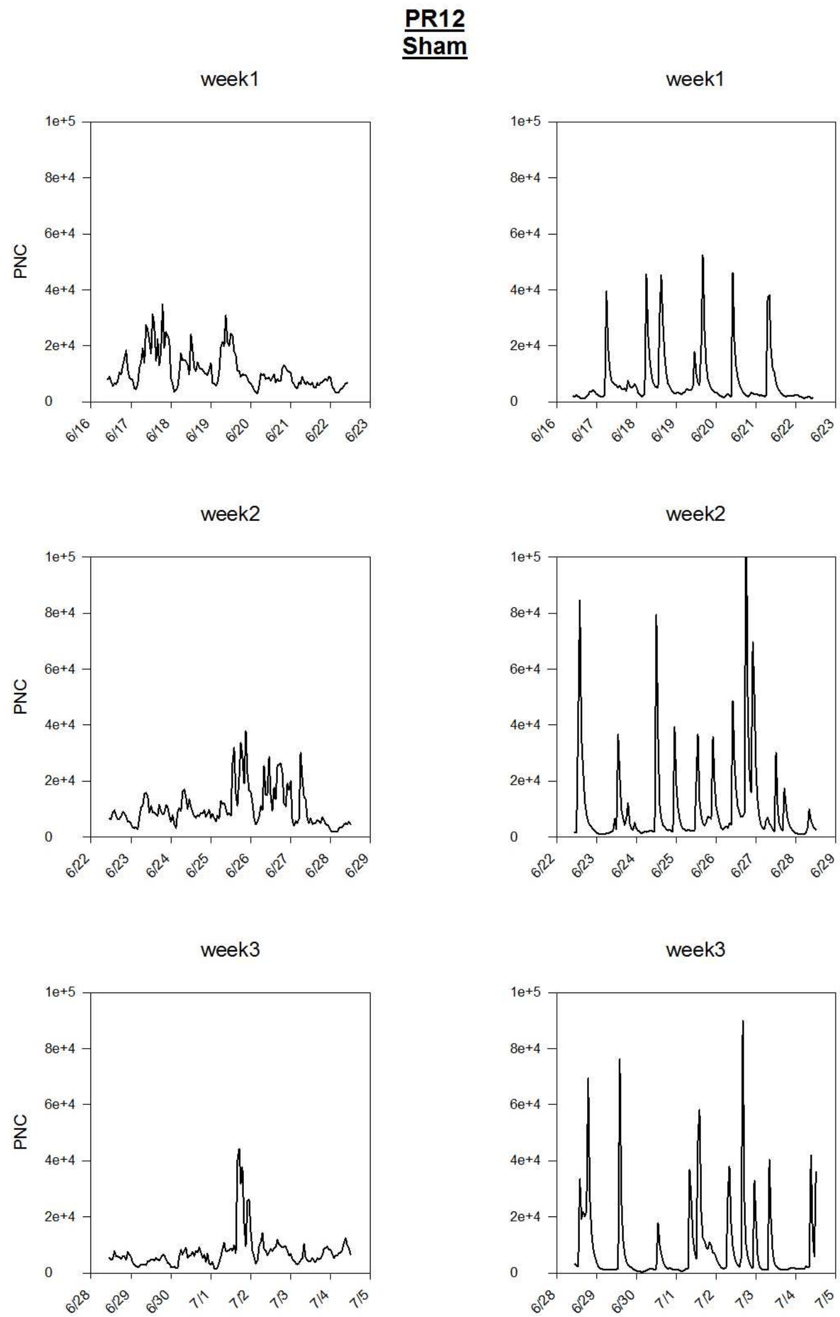
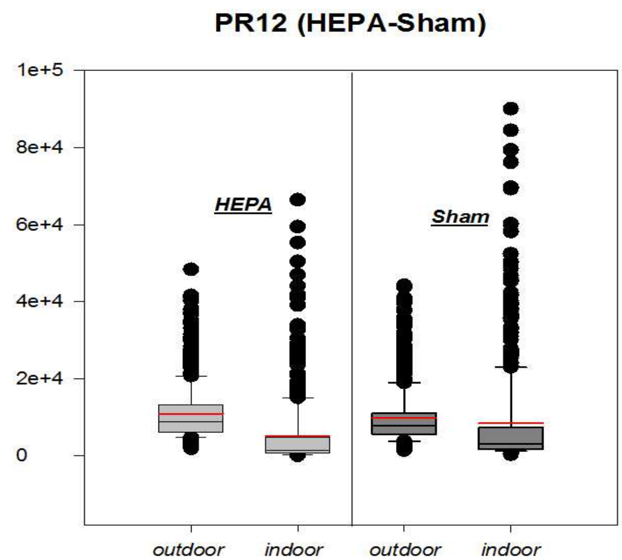


Figure 46. Weekly PNC variations for PR12 during sham filtration



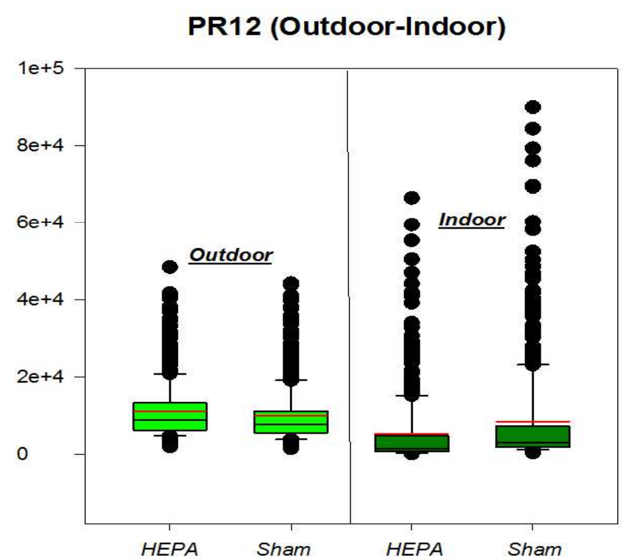


Figure 47. Boxplot for PNC variations for PR12 during HEPA and sham filtration

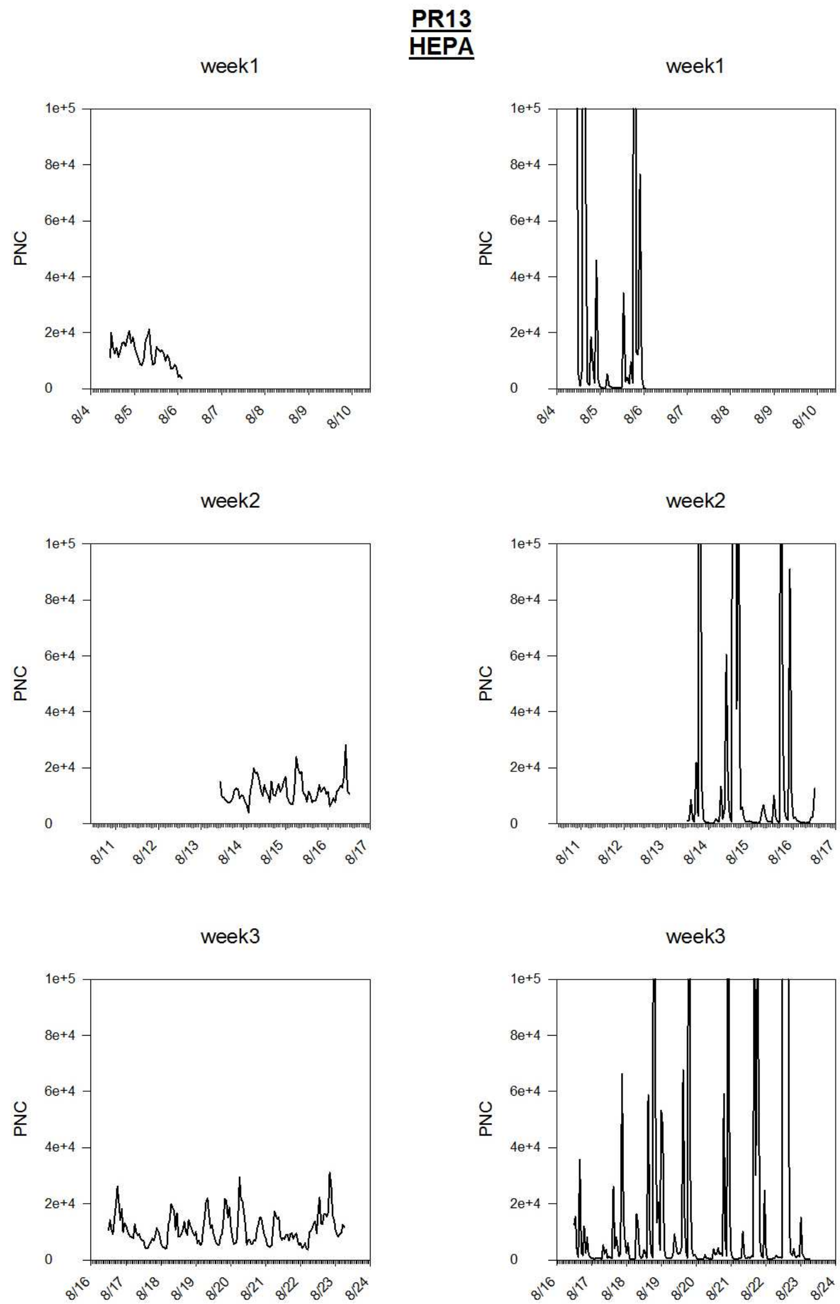


Figure 48. Weekly PNC variations for PR13 during HEPA filtration

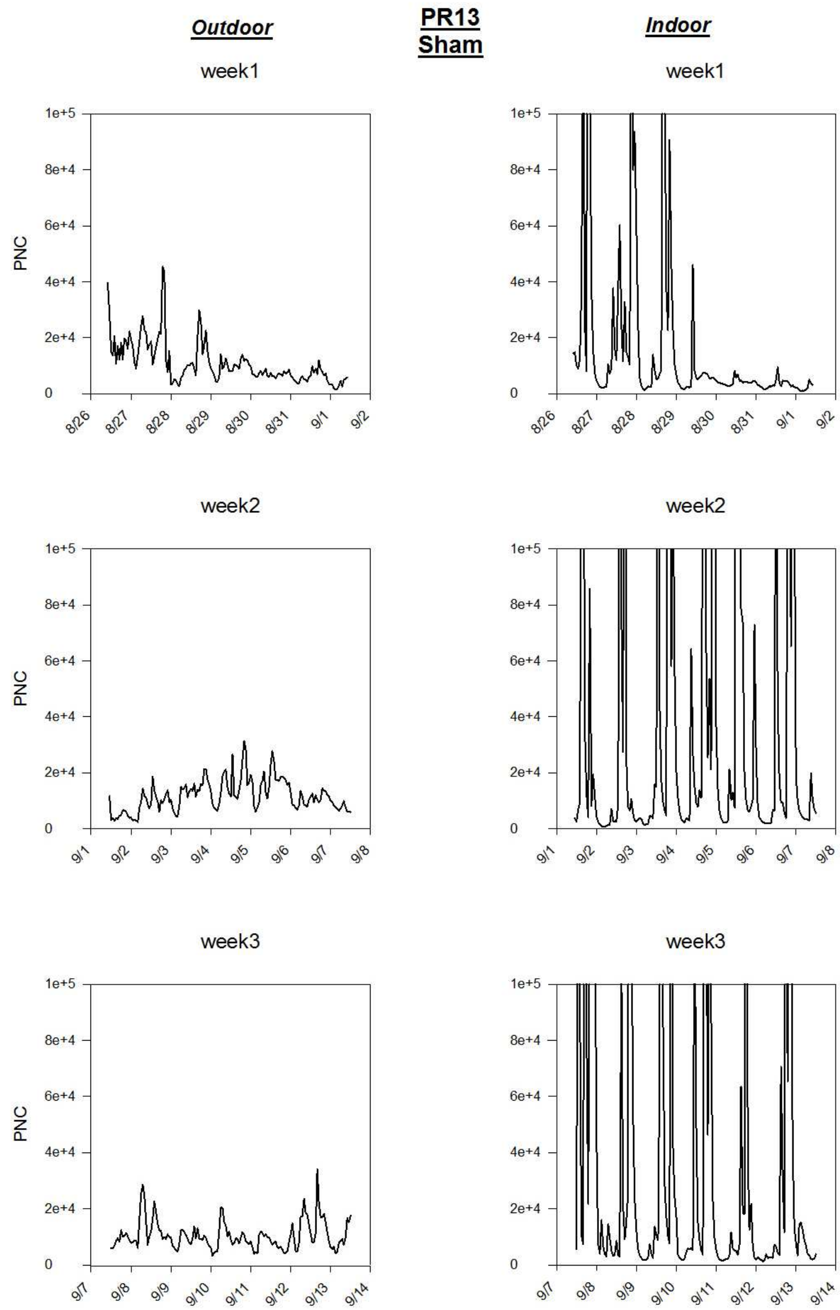


Figure 49. Weekly PNC variations for PR13 during sham filtration

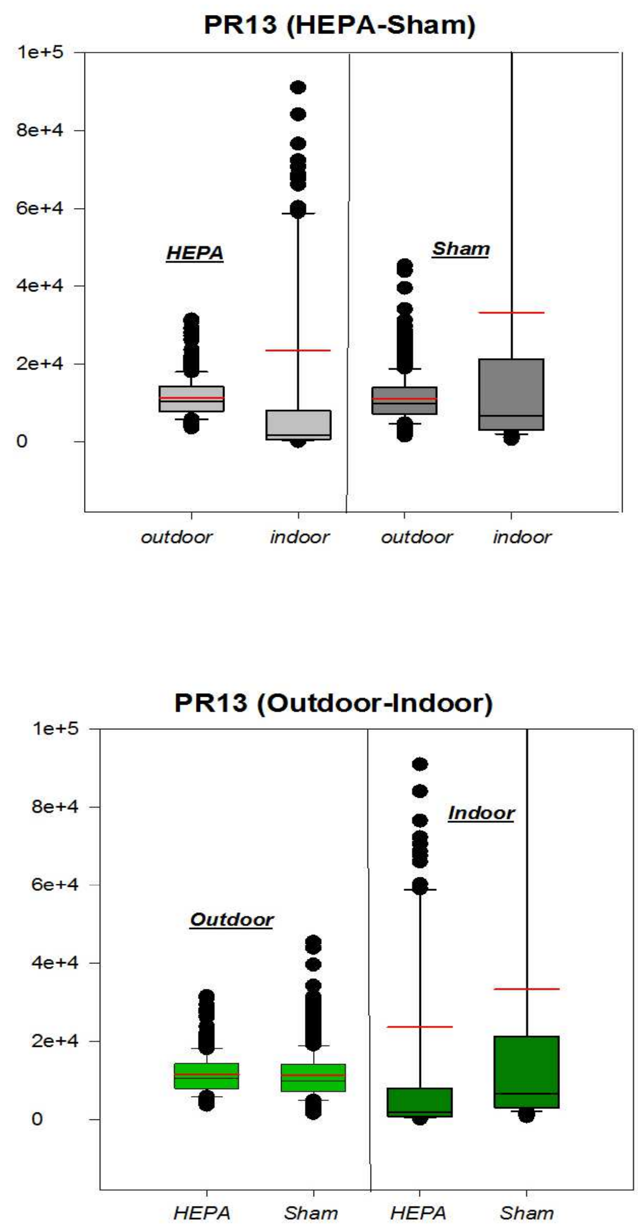


Figure 50. Boxplot for PNC variations for PR13 during HEPA and sham filtration

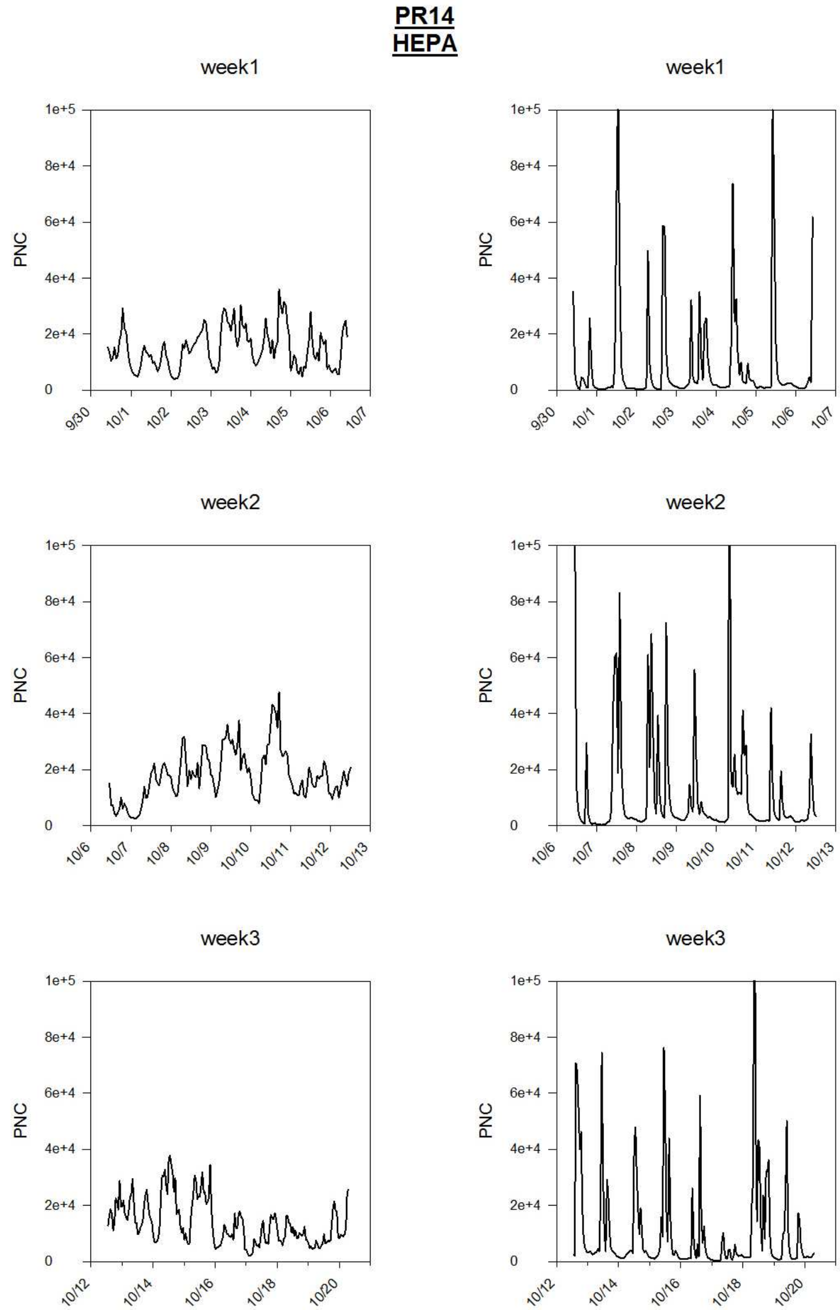


Figure 51. Weekly PNC variations for PR14 during HEPA filtration

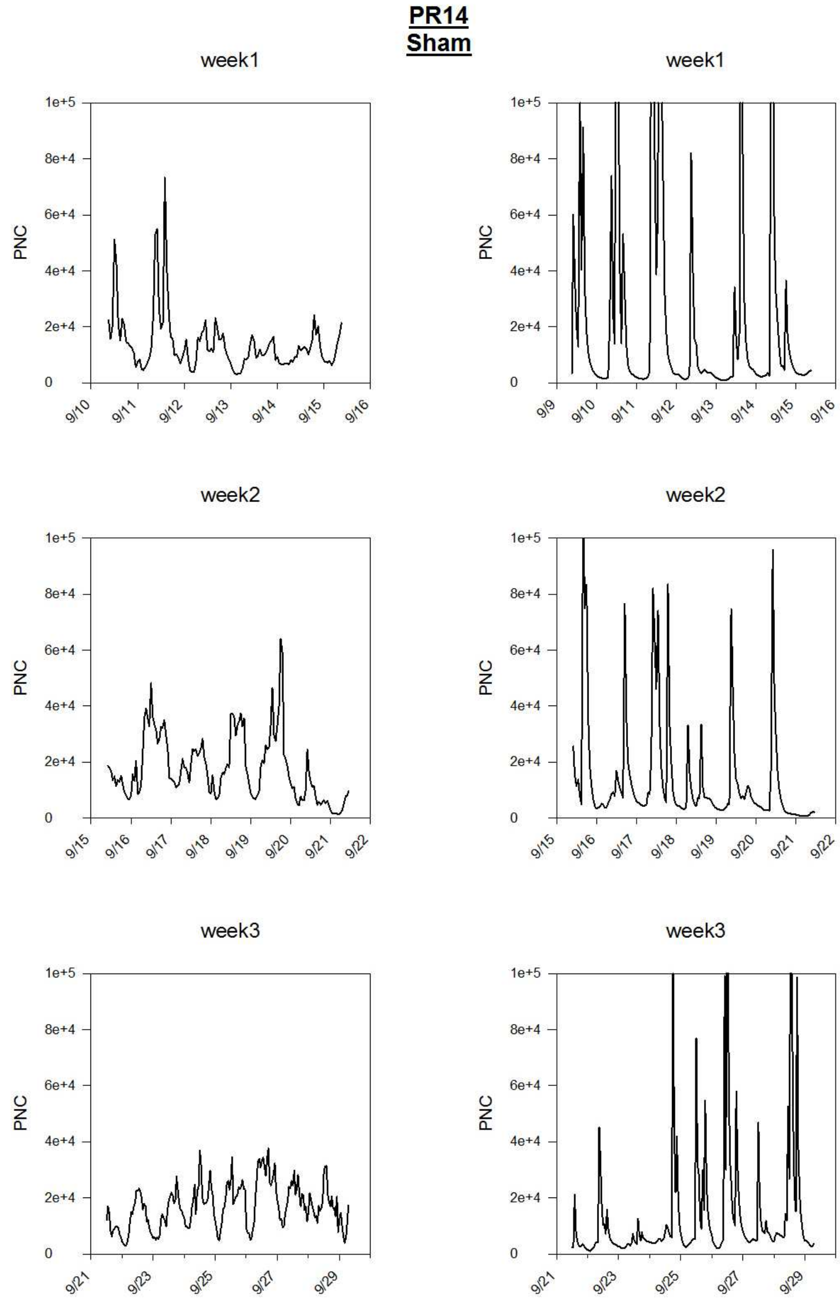
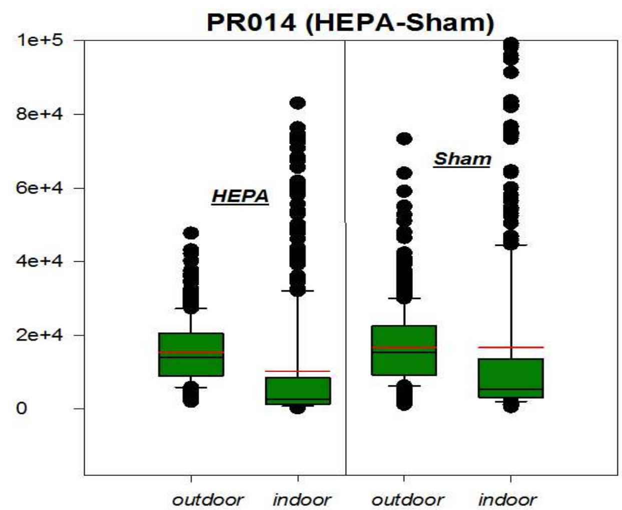


Figure 52. Weekly PNC variations for PR14 during sham filtration



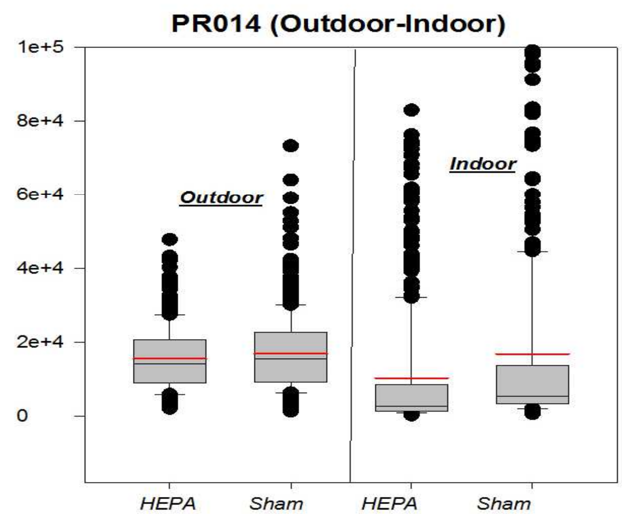


Figure 53. Boxplot for PNC variations for PR14 during HEPA and sham filtration

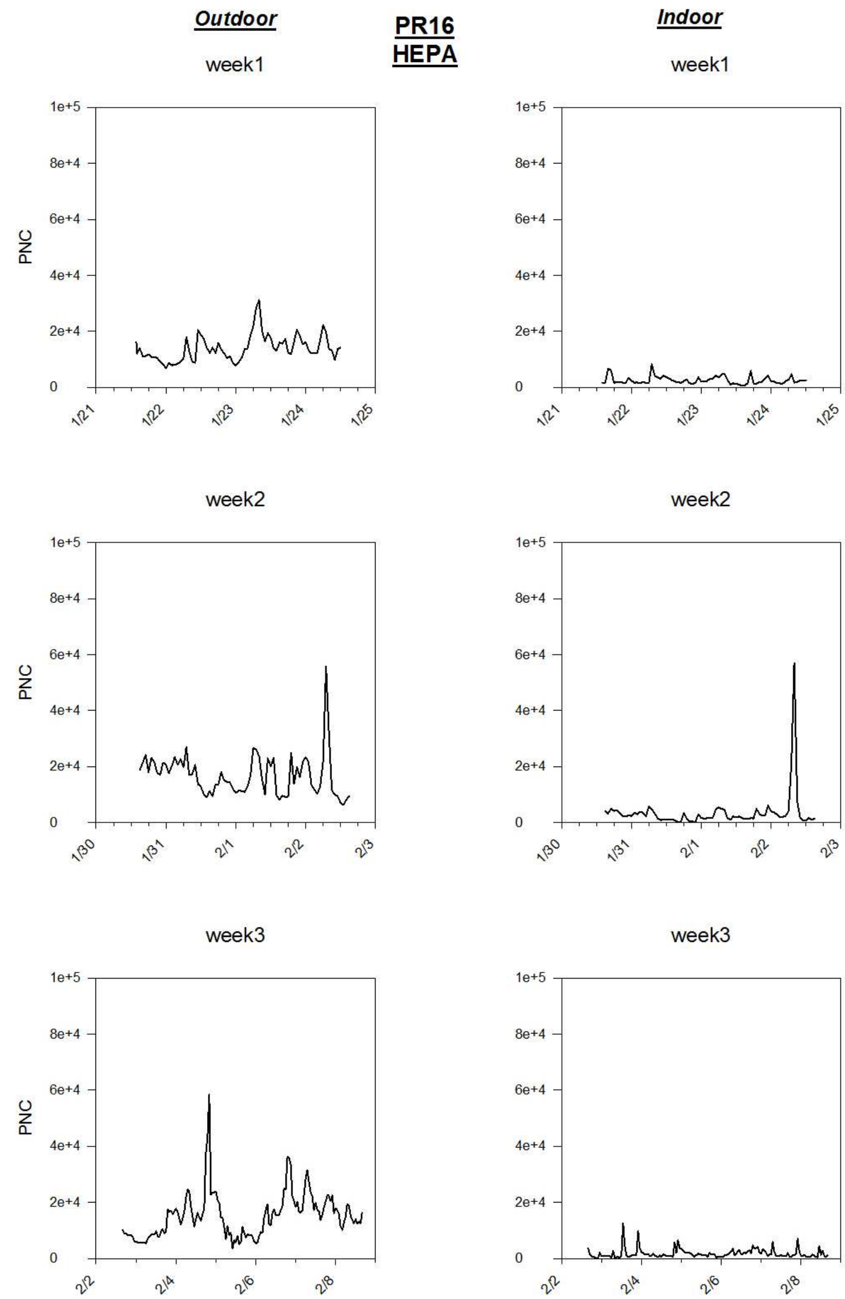


Figure 54. Weekly PNC variations for PR16 during HEPA filtration

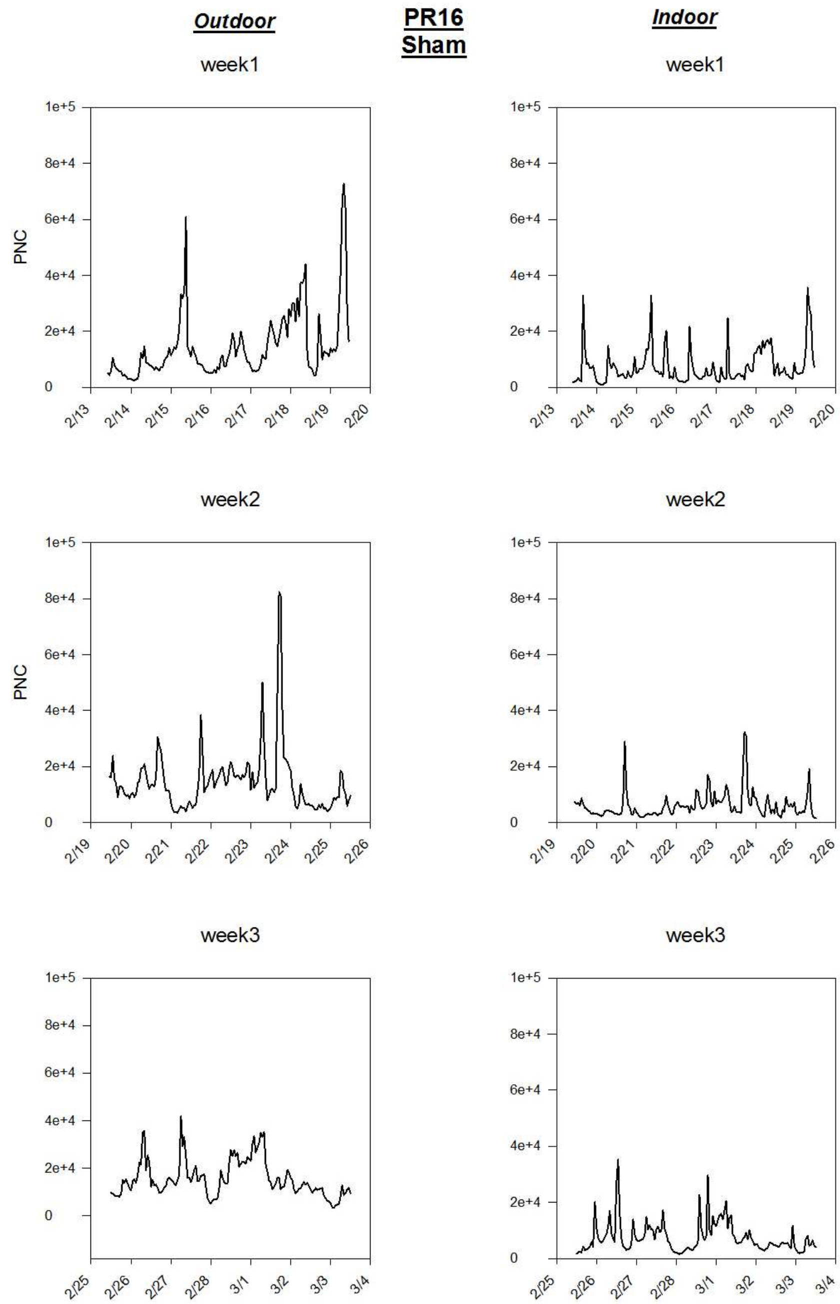
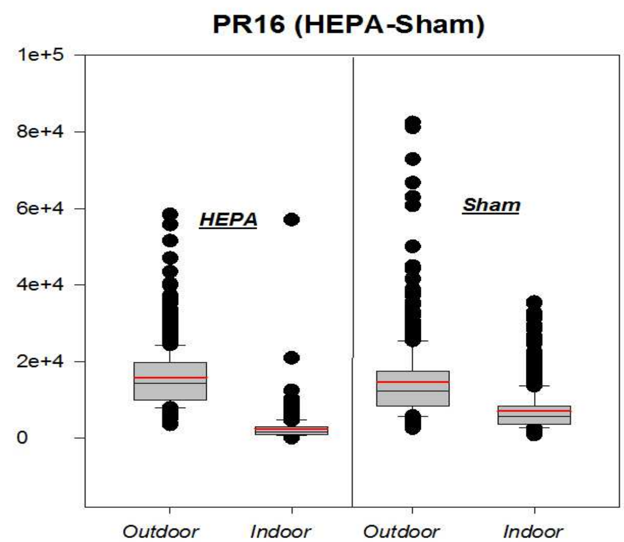


Figure 55. Weekly PNC variations for PR16 during sham filtration



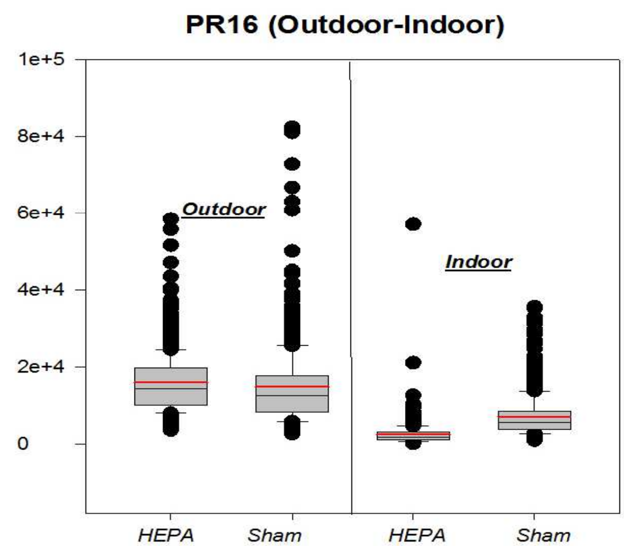


Figure 56. Boxplot for PNC variations for PR16 during HEPA and sham filtration

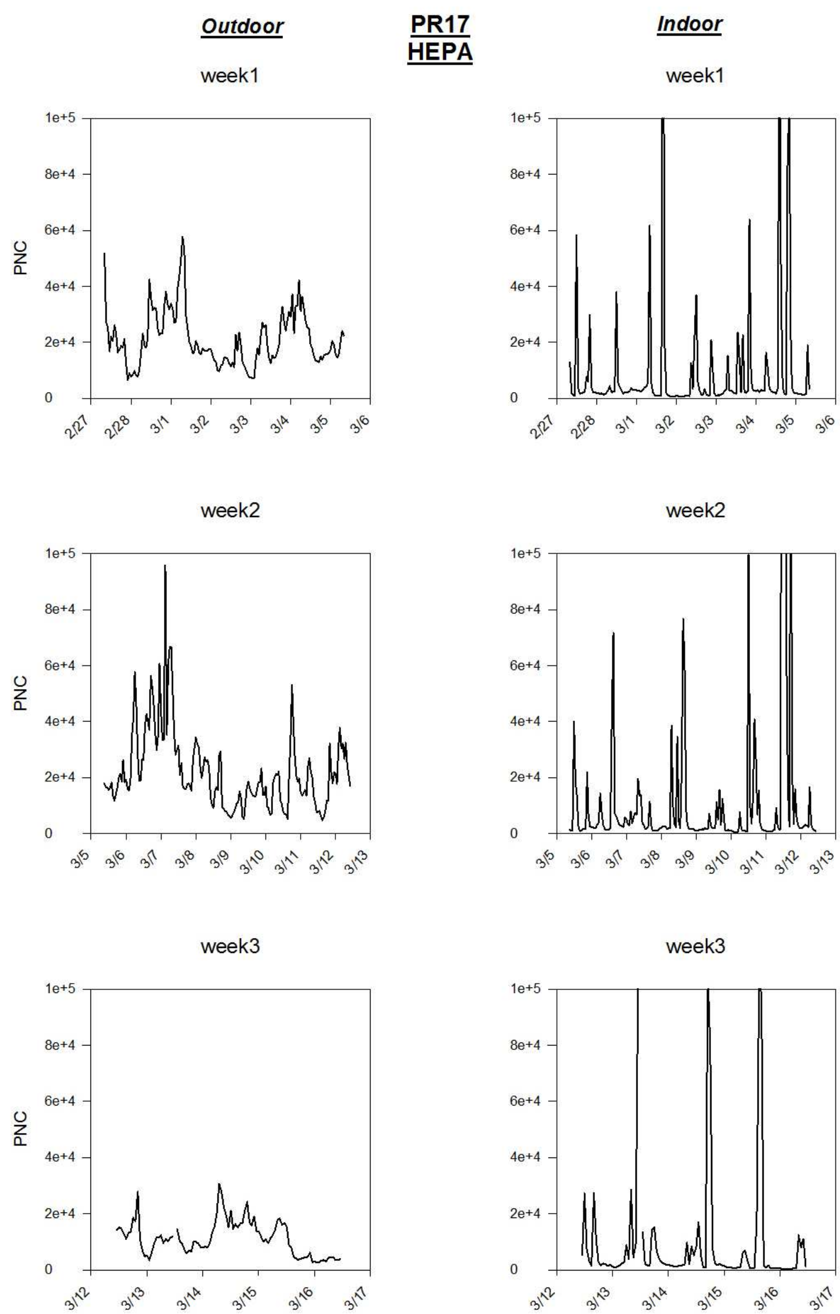


Figure 57. Weekly PNC variations for PR17 during HEPA filtration

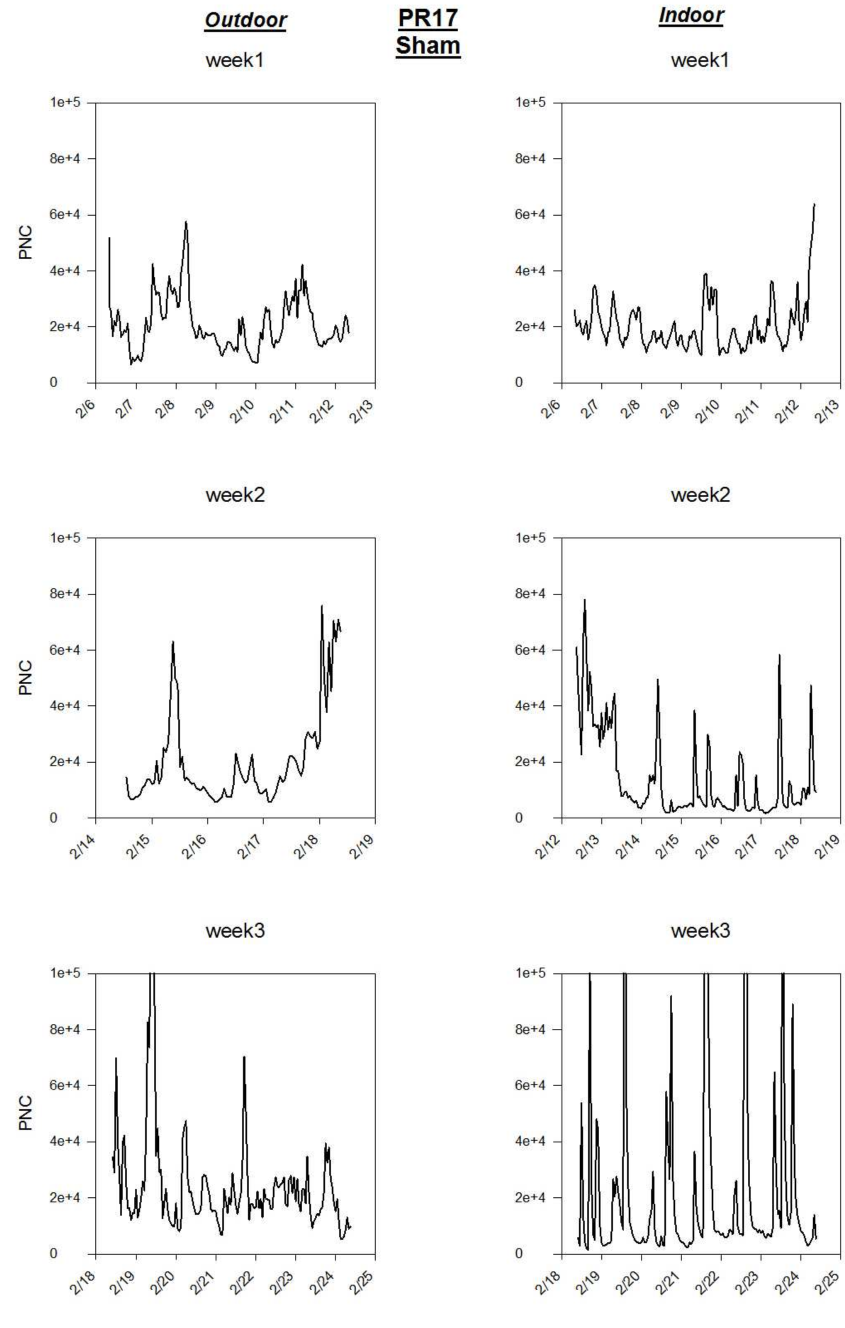


Figure 58. Weekly PNC variations for PR17 during sham filtration

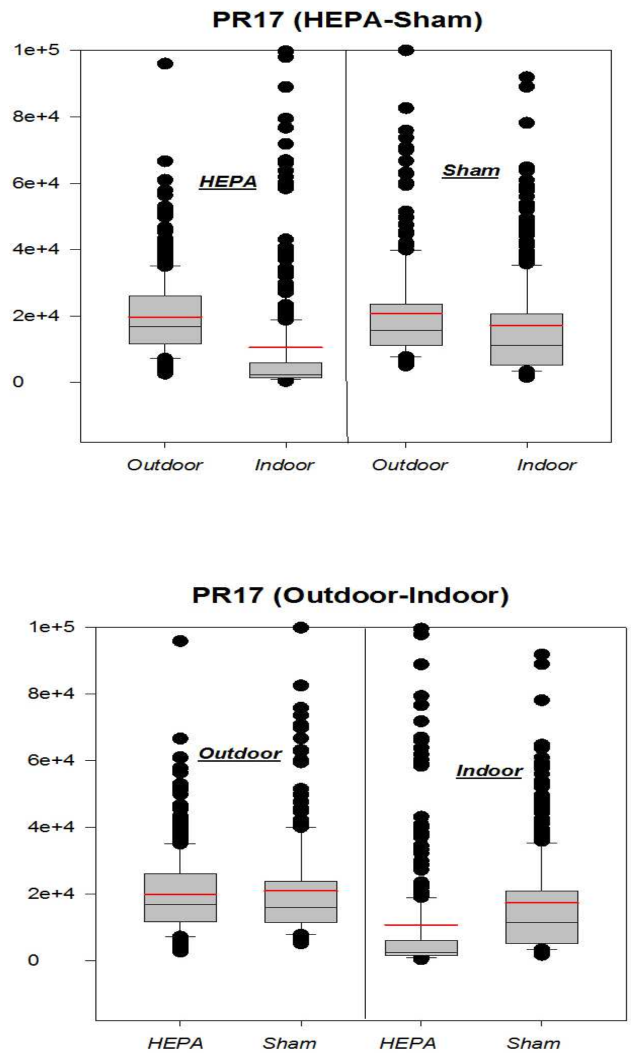


Figure 59. Boxplot for PNC variations for PR17 during HEPA and sham filtration

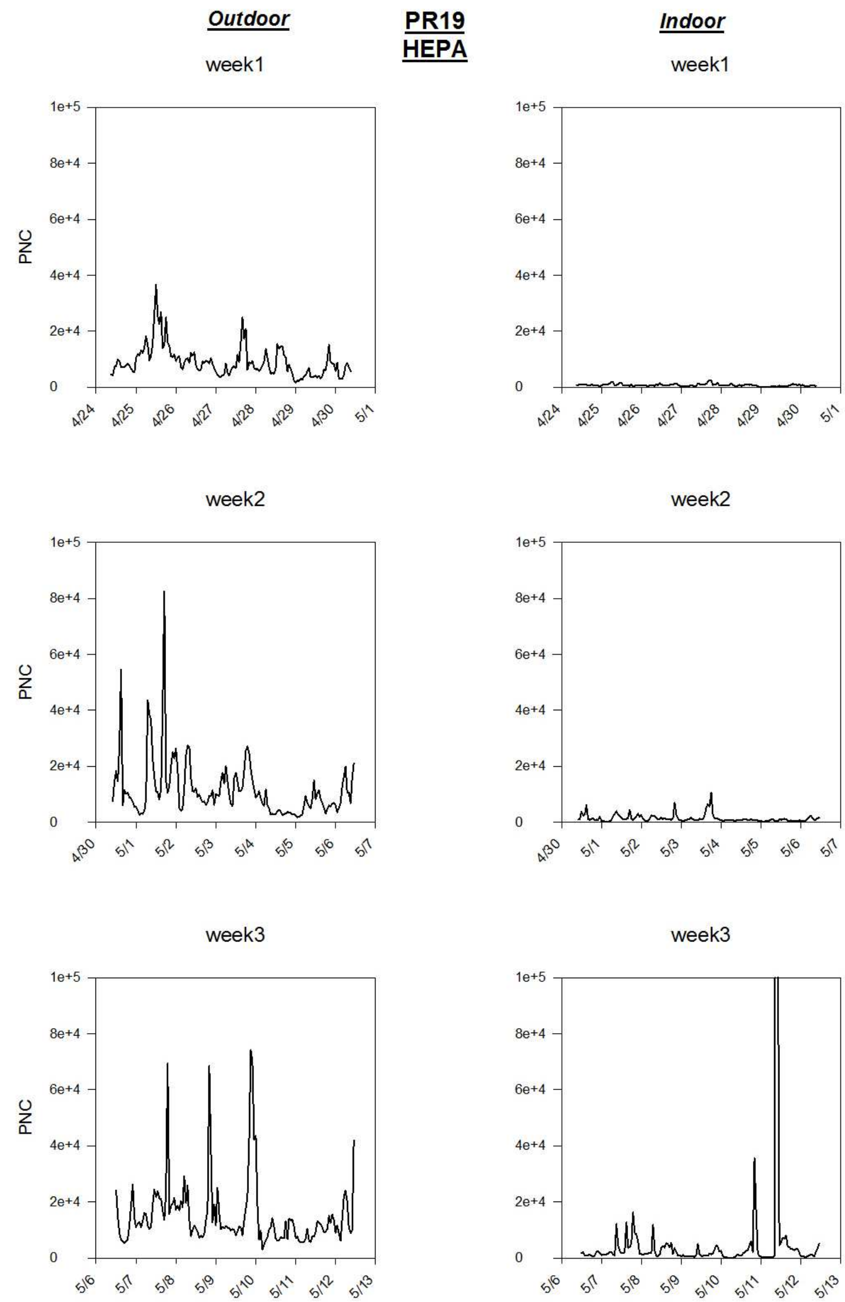


Figure 60. Weekly PNC variations for PR19 during HEPA filtration

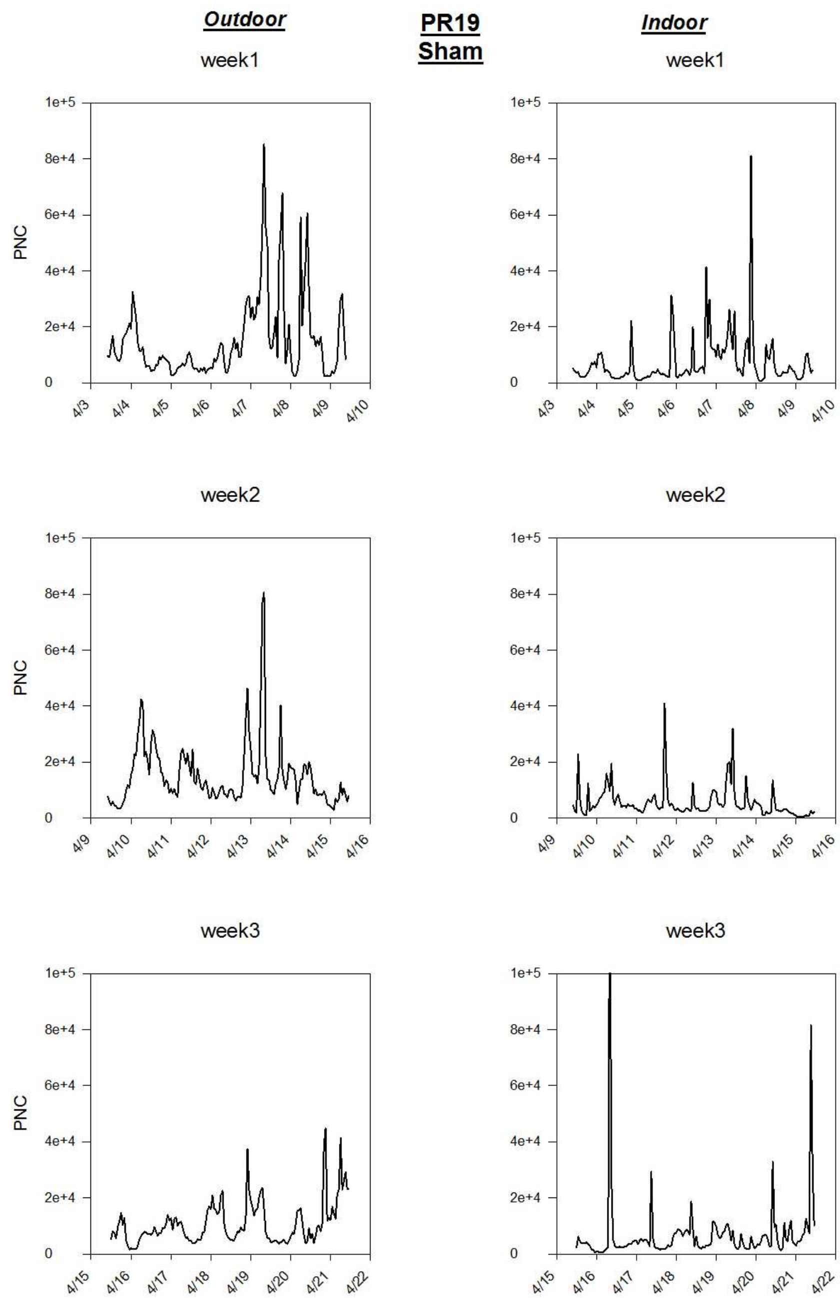
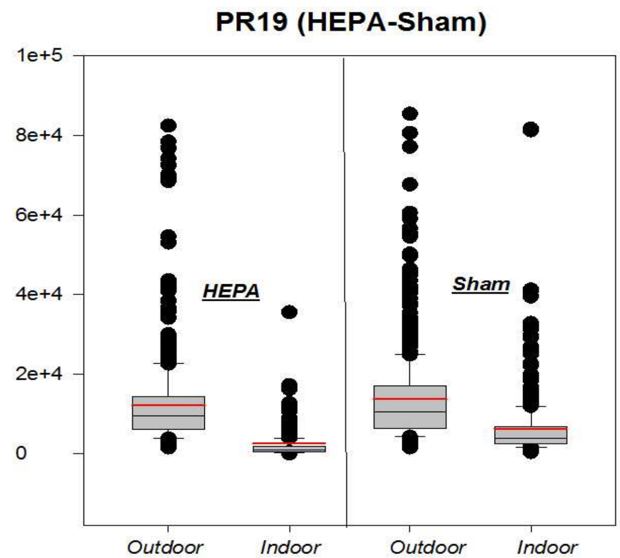


Figure 61. Weekly PNC variations for PR19 during sham filtration



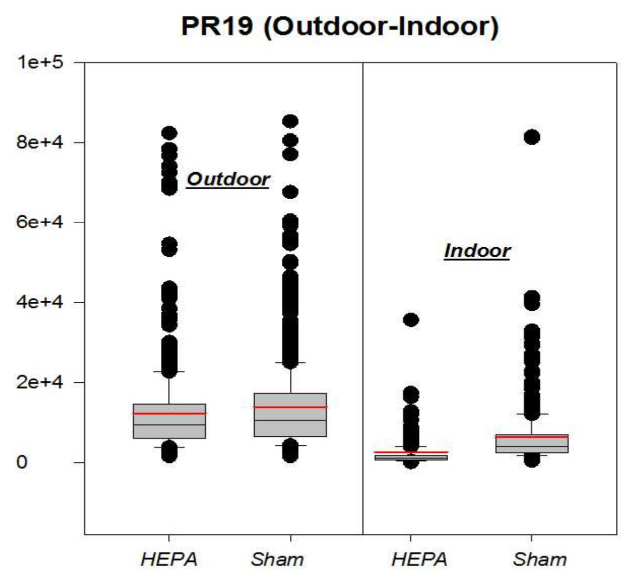


Figure 62. Boxplot for PNC variations for PR19 during HEPA and sham filtration

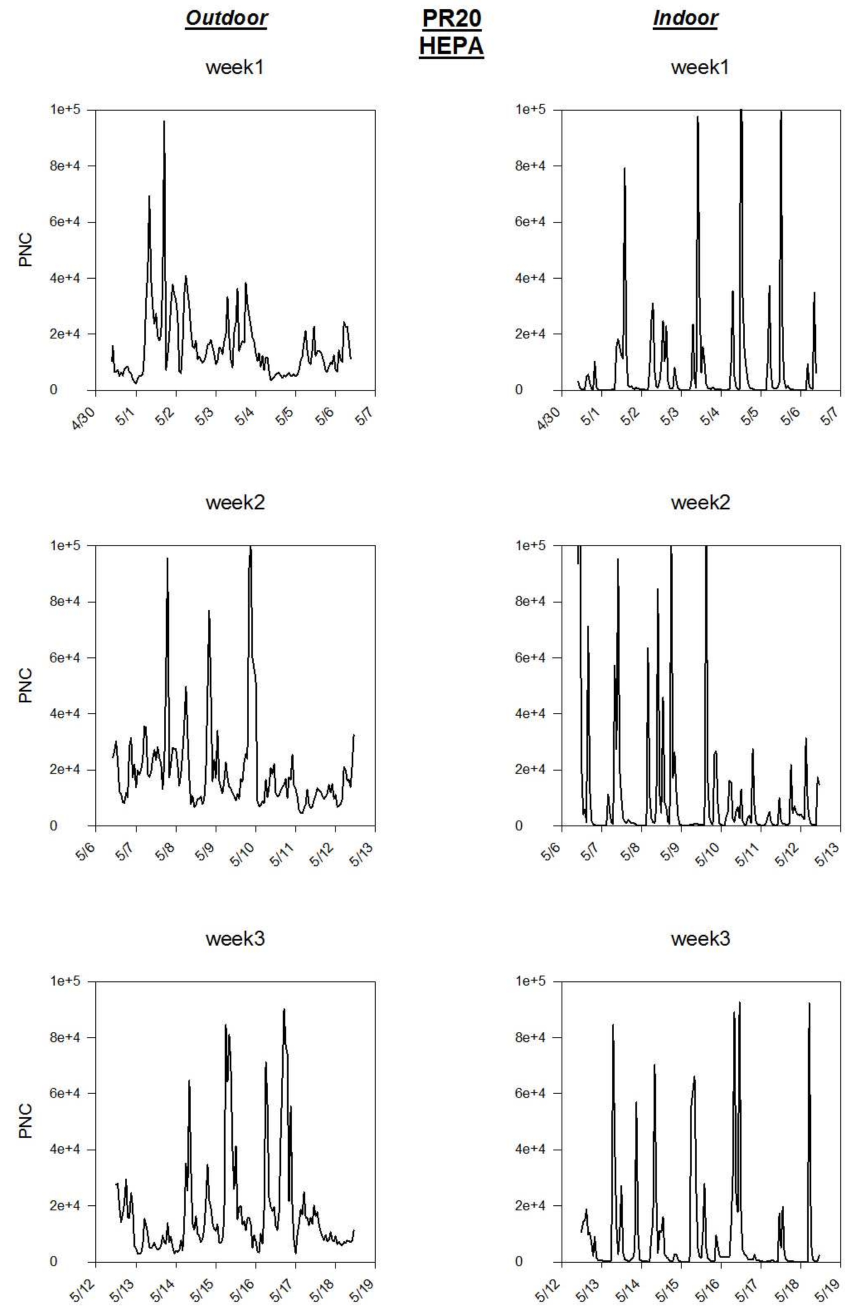


Figure 63. Weekly PNC variations for PR20 during HEPA filtration

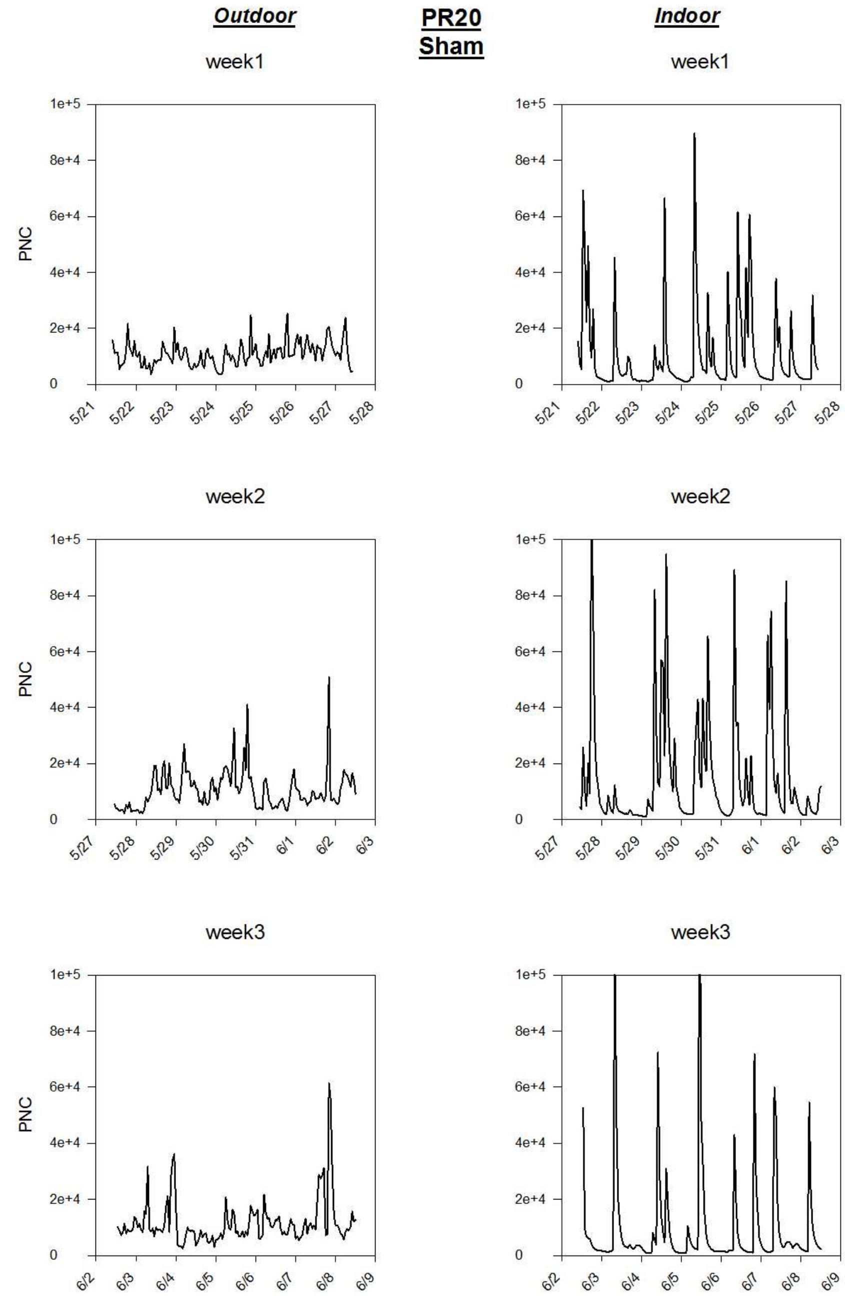
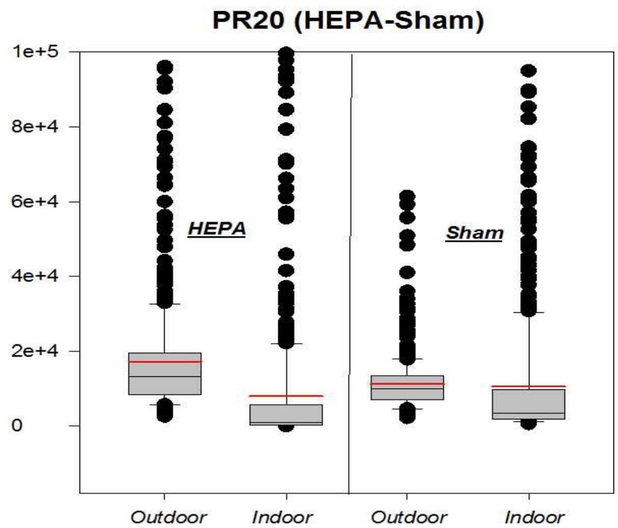


Figure 64. Weekly PNC variations for PR20 during sham filtration



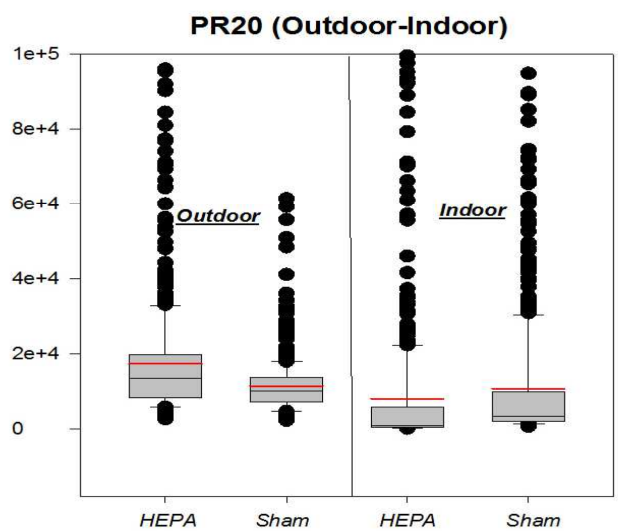


Figure 65. Boxplot for PNC variations for PR20 during HEPA and sham filtration

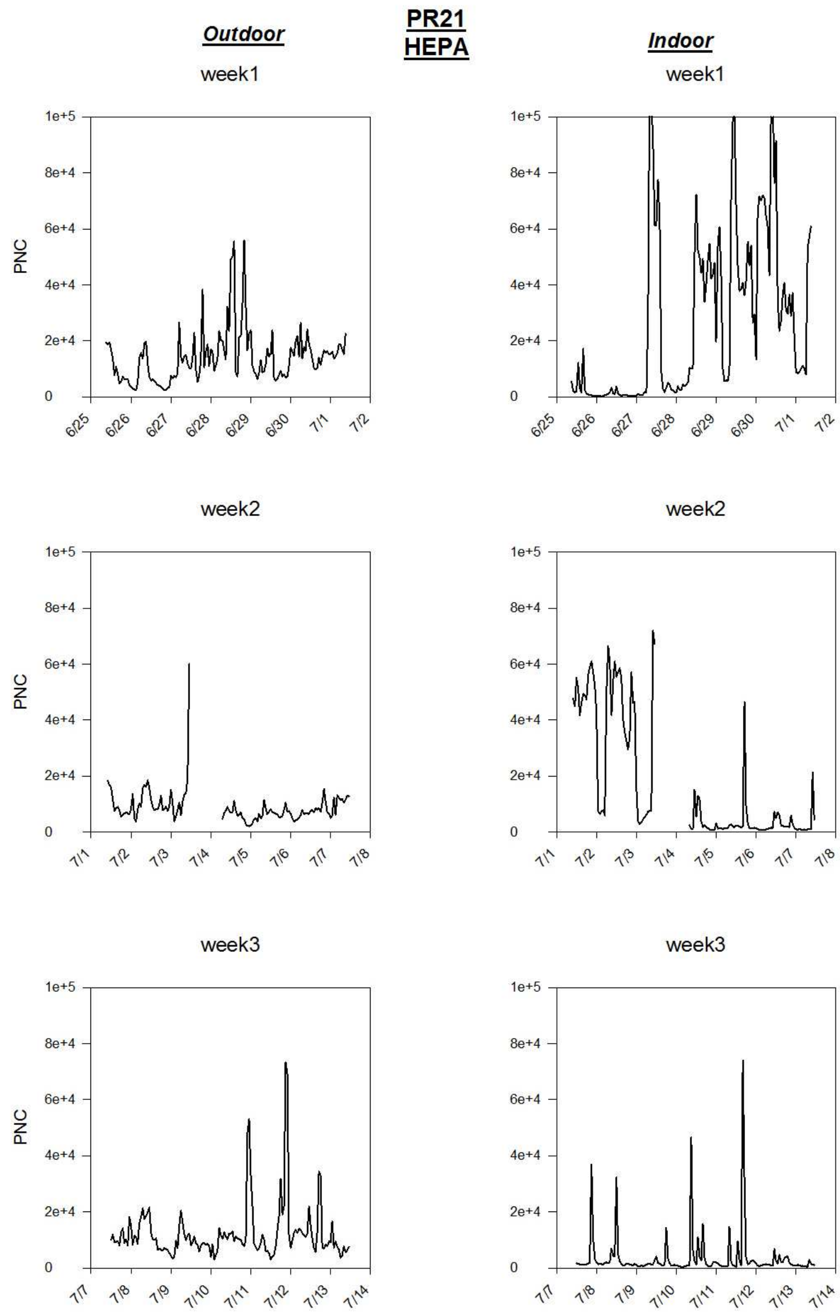


Figure 66. Weekly PNC variations for PR21 during HEPA filtration

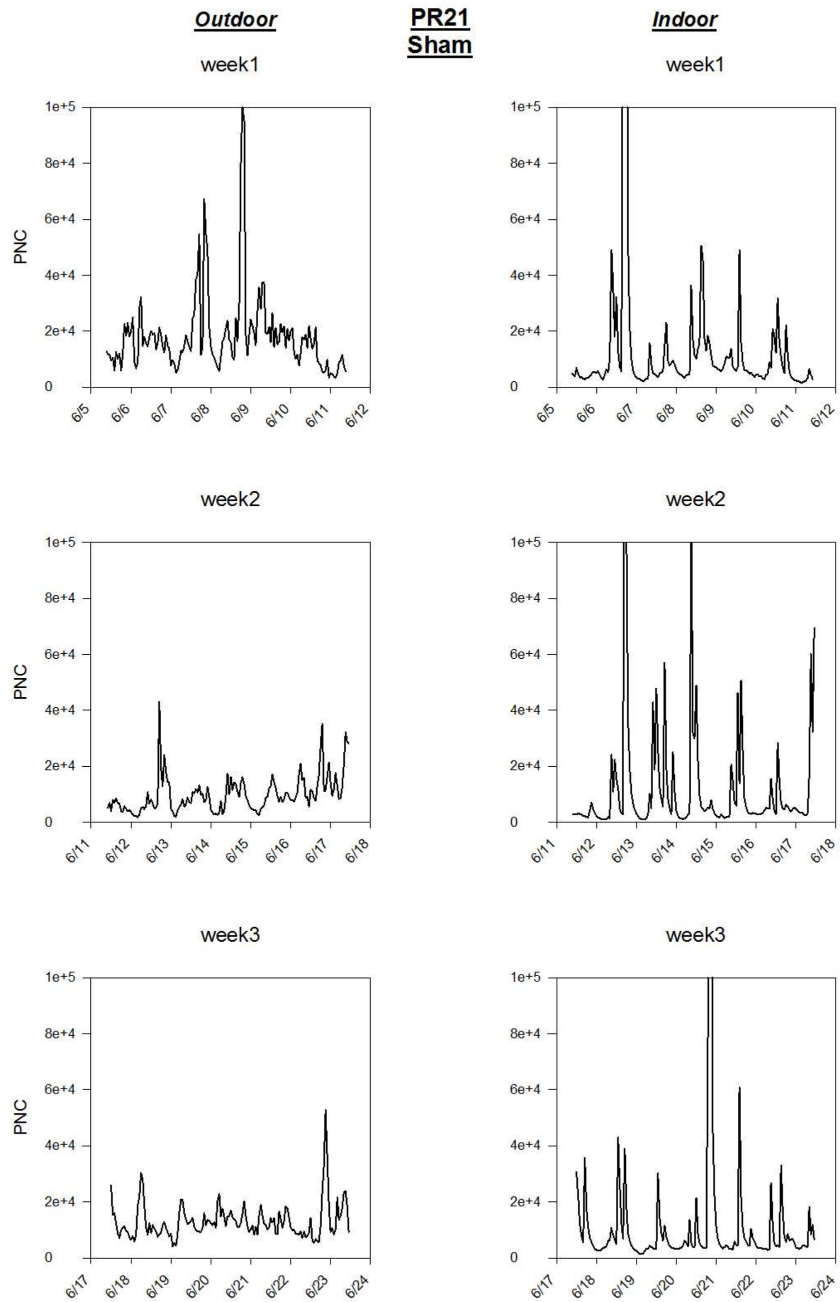
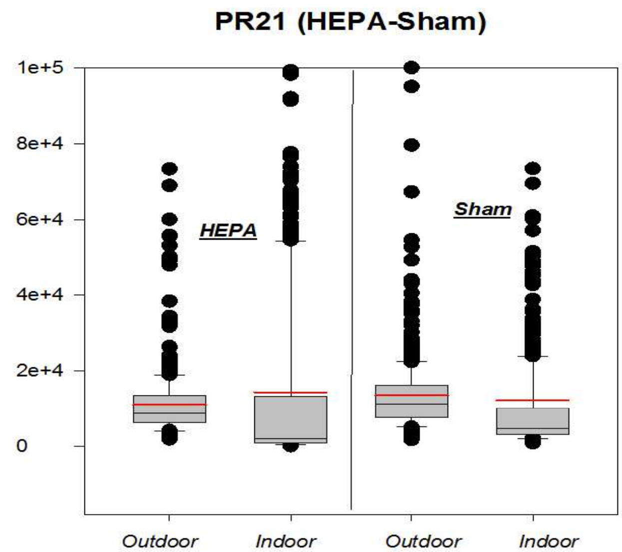


Figure 67. Weekly PNC variations for PR21 during sham filtration



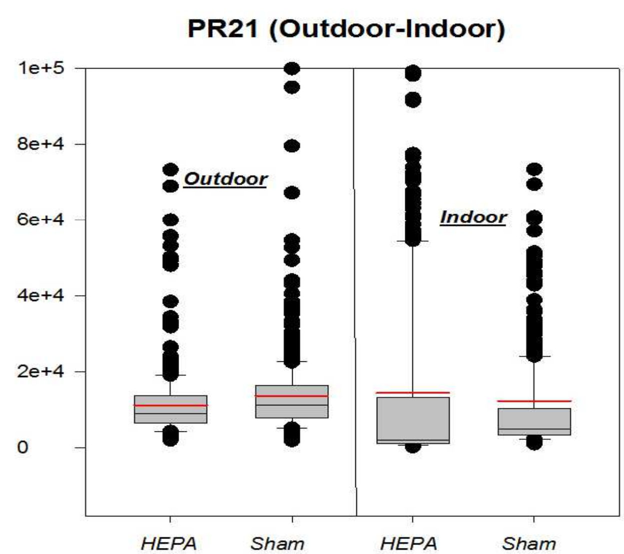


Figure 68. Boxplot for PNC variations for PR21 during HEPA and sham filtration

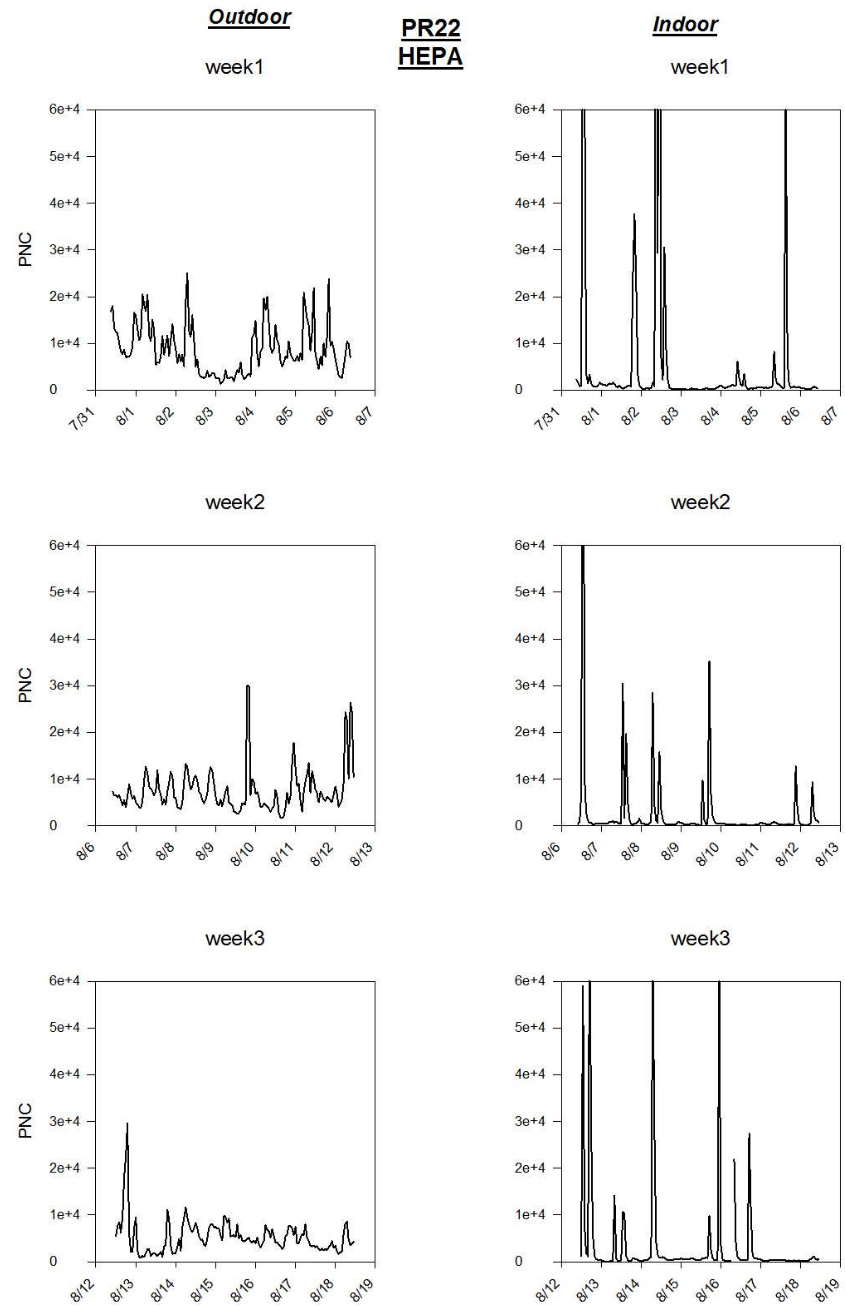


Figure 69. Weekly PNC variations for PR22 during HEPA filtration

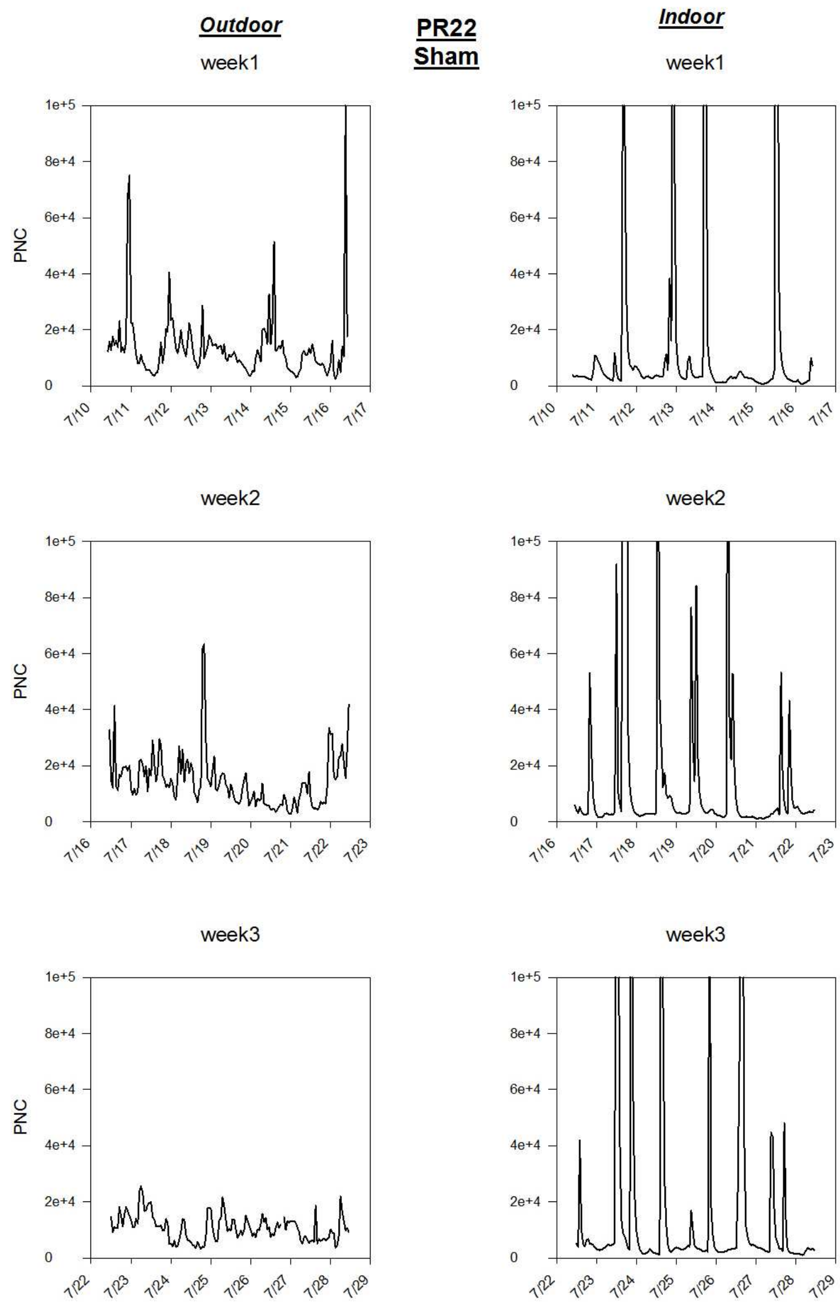
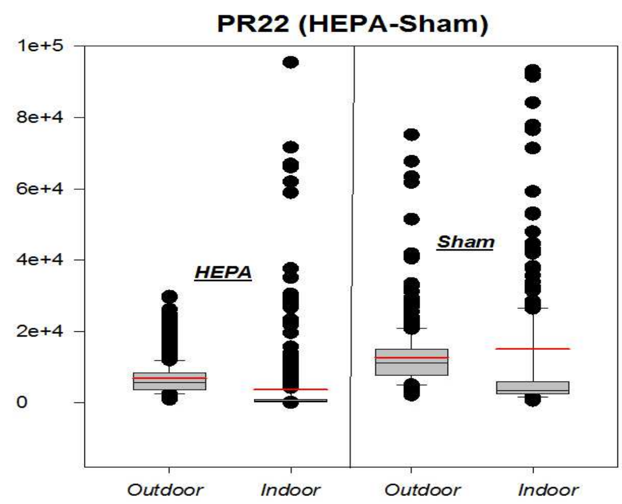


Figure 70. Weekly PNC variations for PR22 during sham filtration



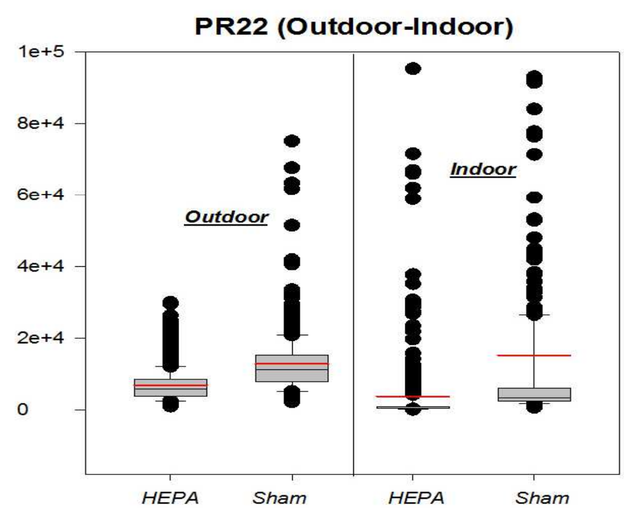


Figure 71. Boxplot for PNC variations for PR22 during HEPA and sham filtration

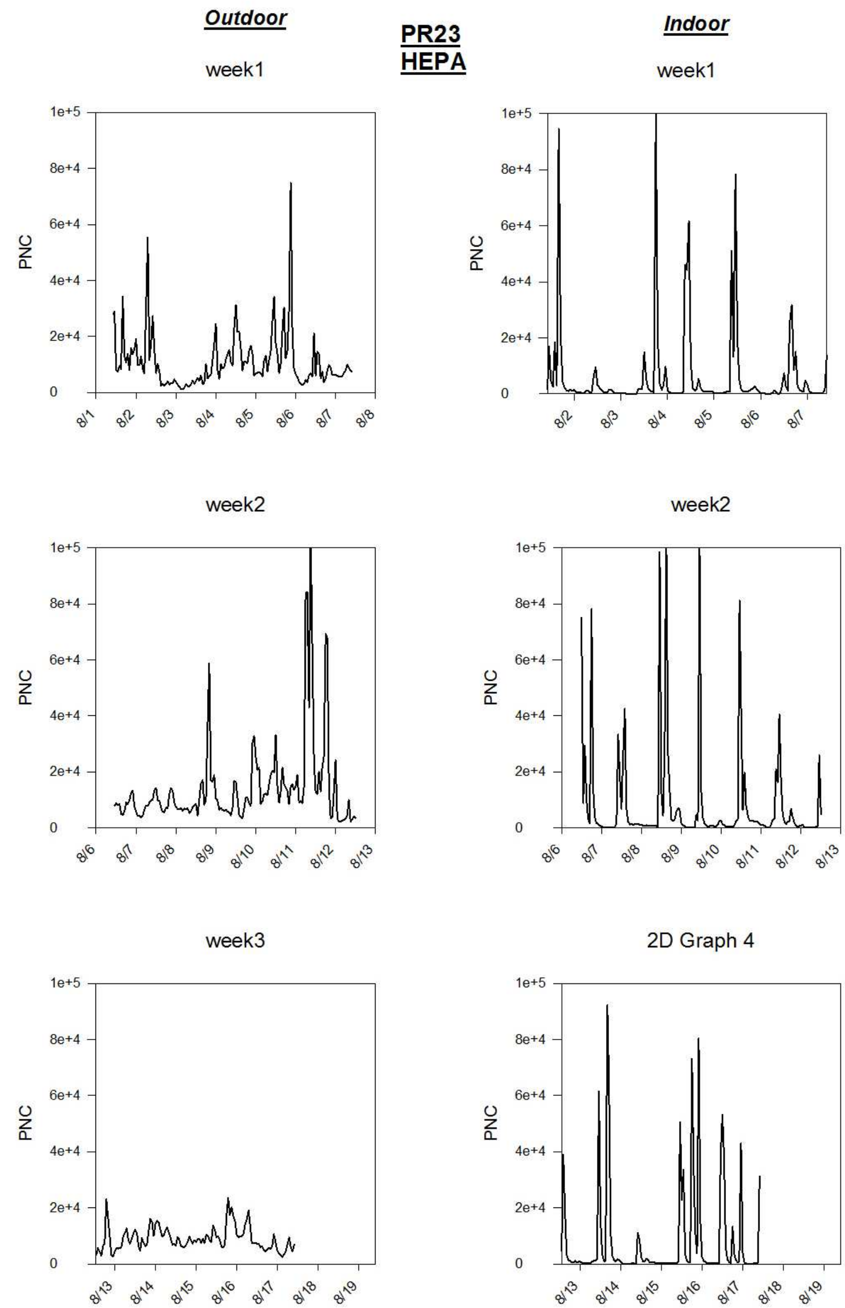


Figure 72. Weekly PNC variations for PR23 during HEPA filtration

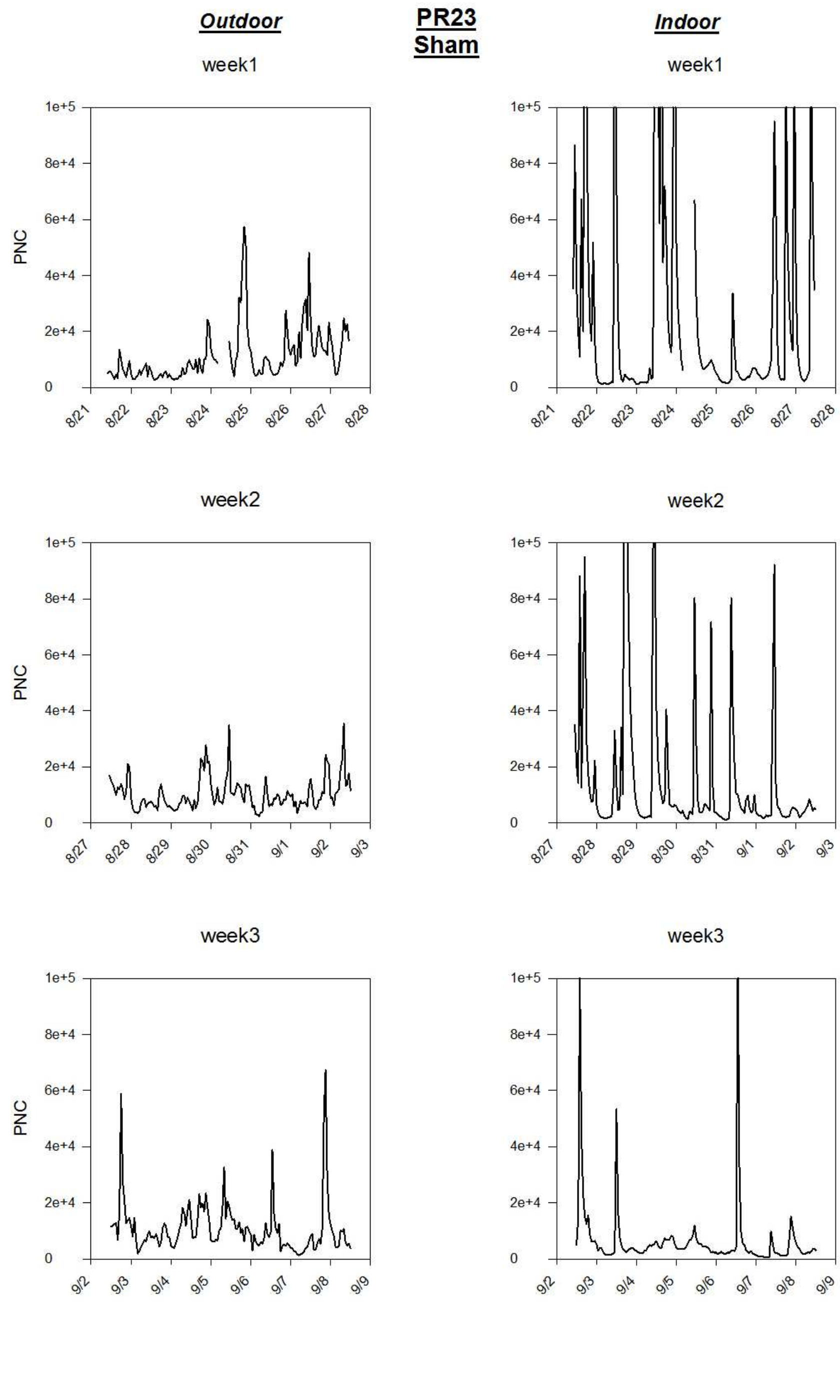
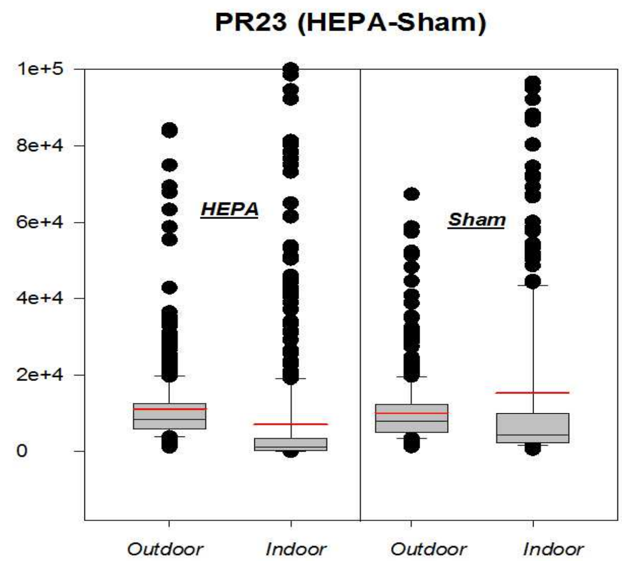


Figure 73. Weekly PNC variations for PR23 during sham filtration



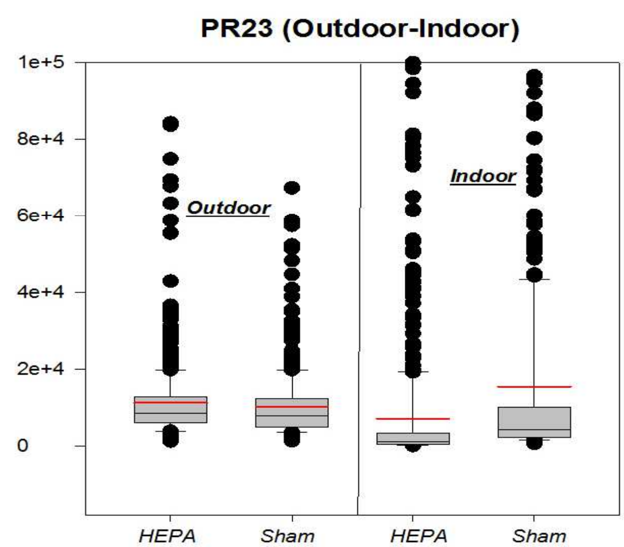


Figure 74. Boxplot for PNC variations for PR23 during HEPA and sham filtration

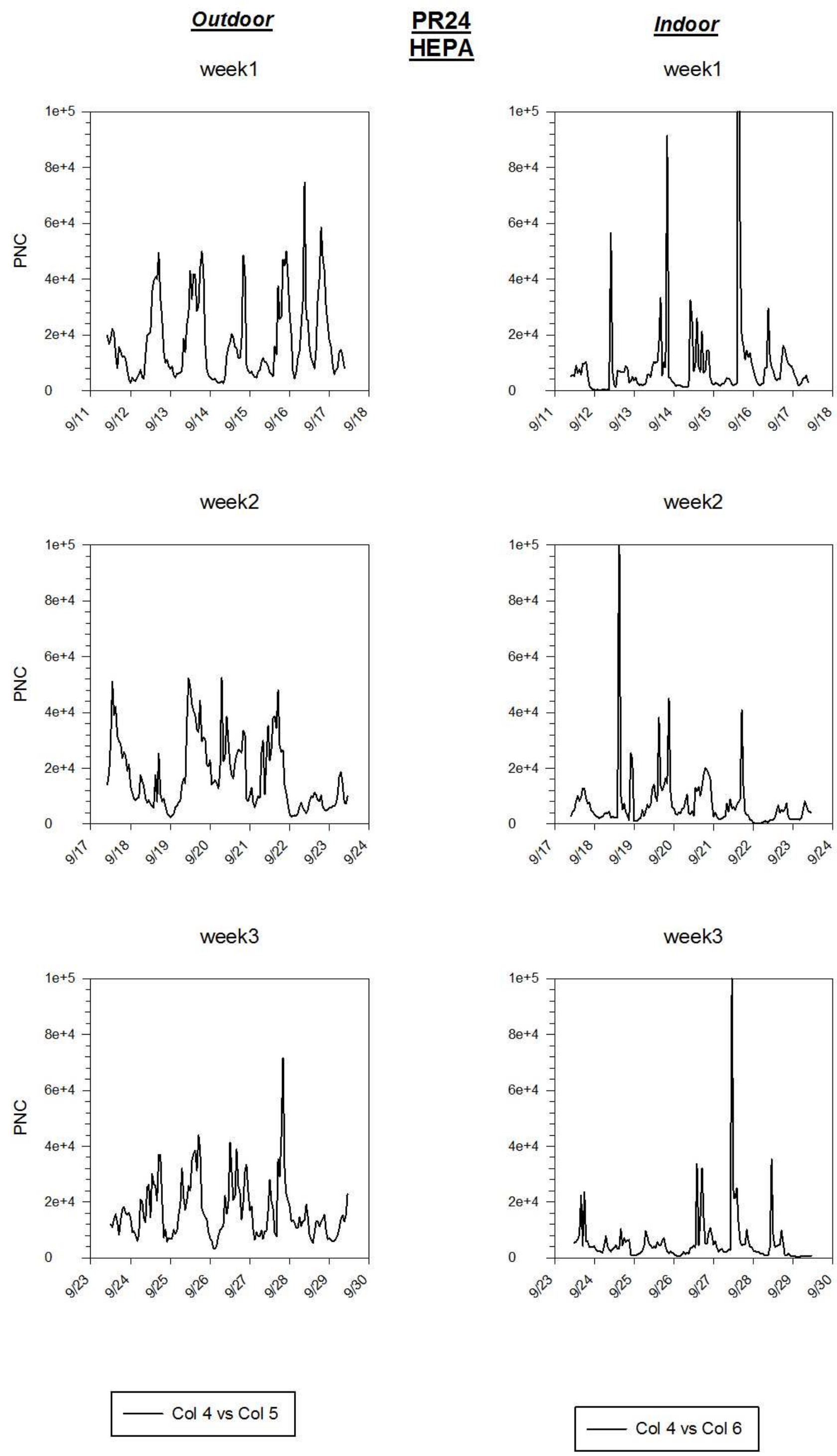


Figure 75. Weekly PNC variations for PR24 during HEPA filtration

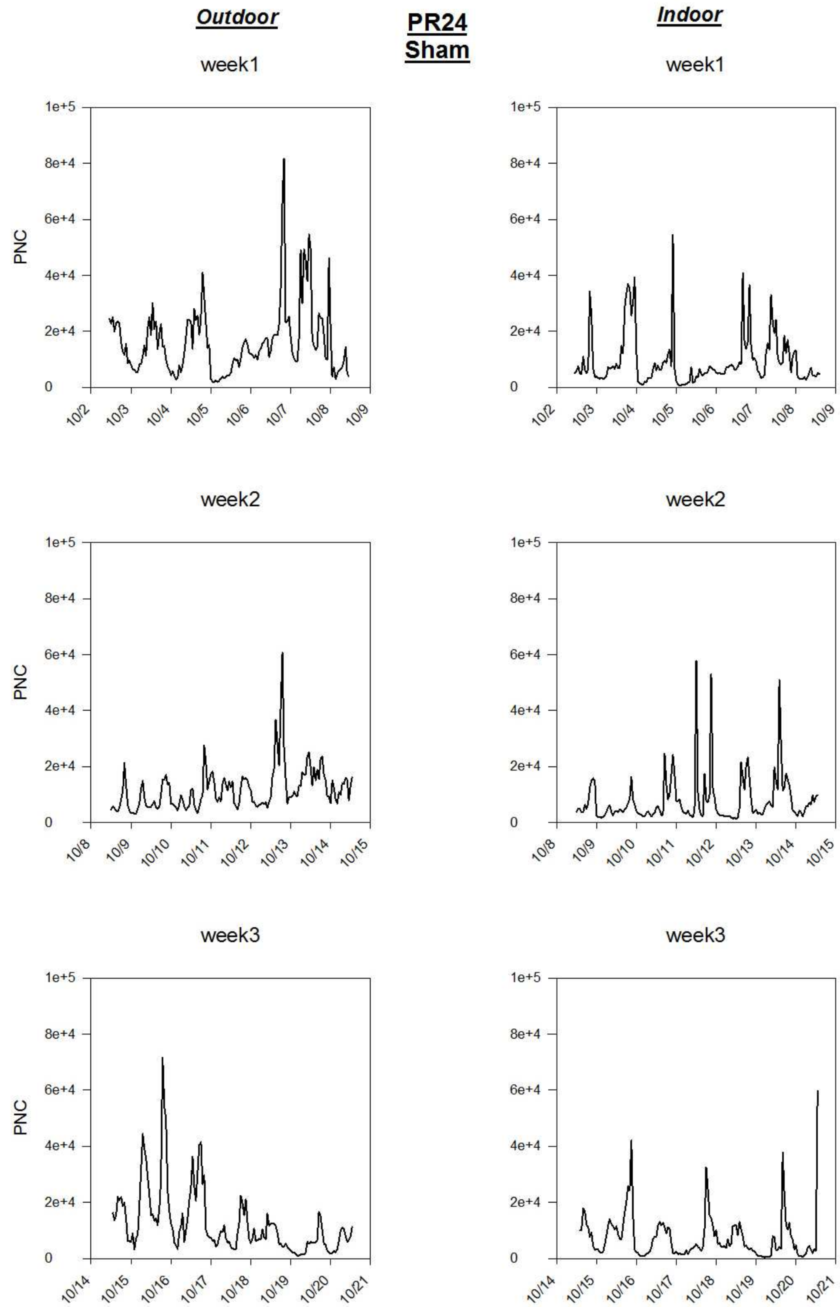


Figure 76. Weekly PNC variations for PR24 during sham filtration

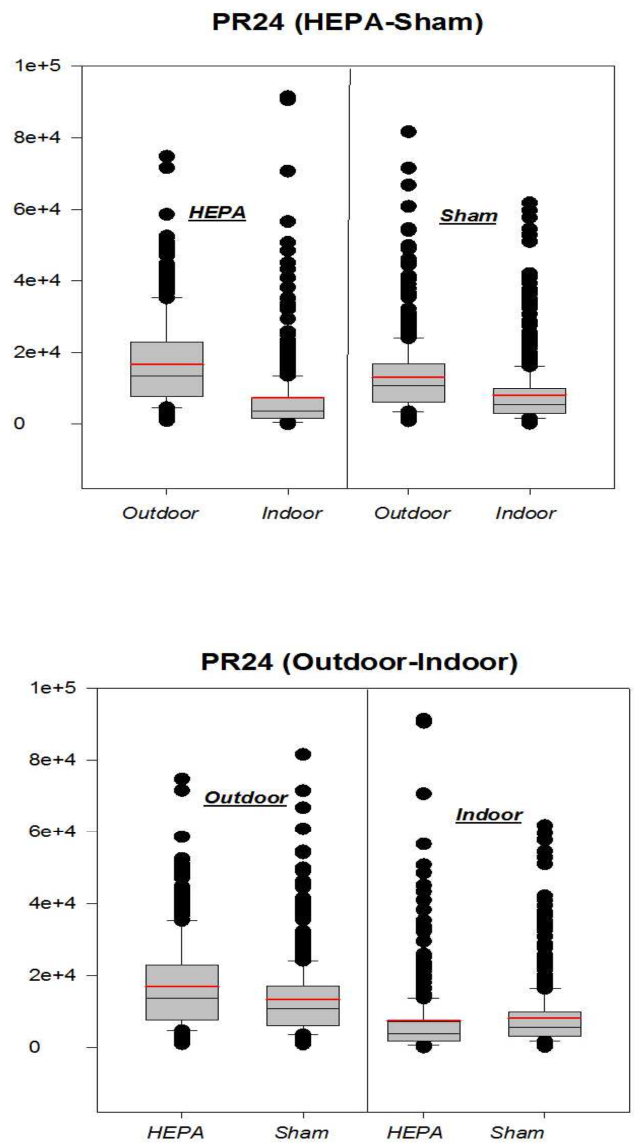


Figure 77. Boxplot for PNC variations for PR24 during HEPA and sham filtration

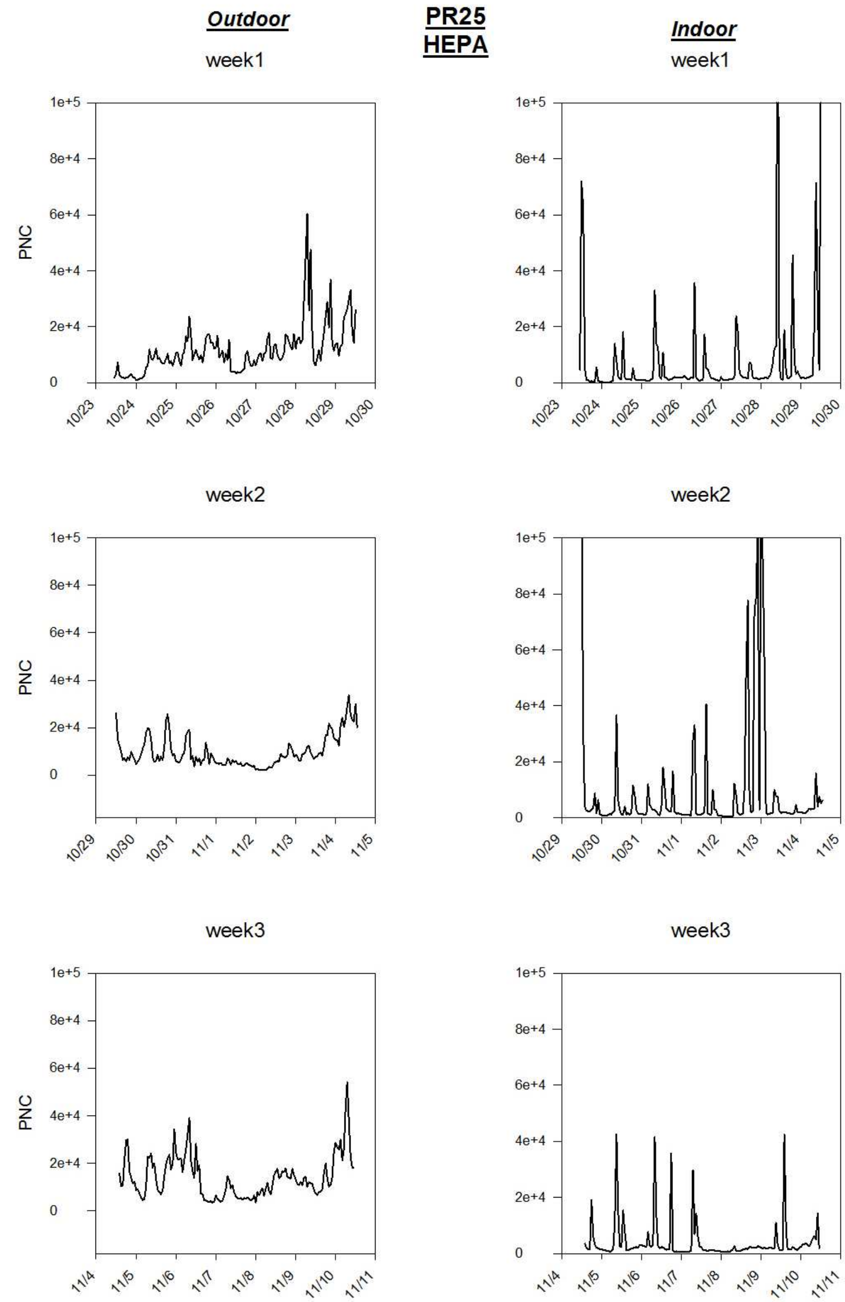


Figure 78. Weekly PNC variations fro PR25 during HEPA filtration

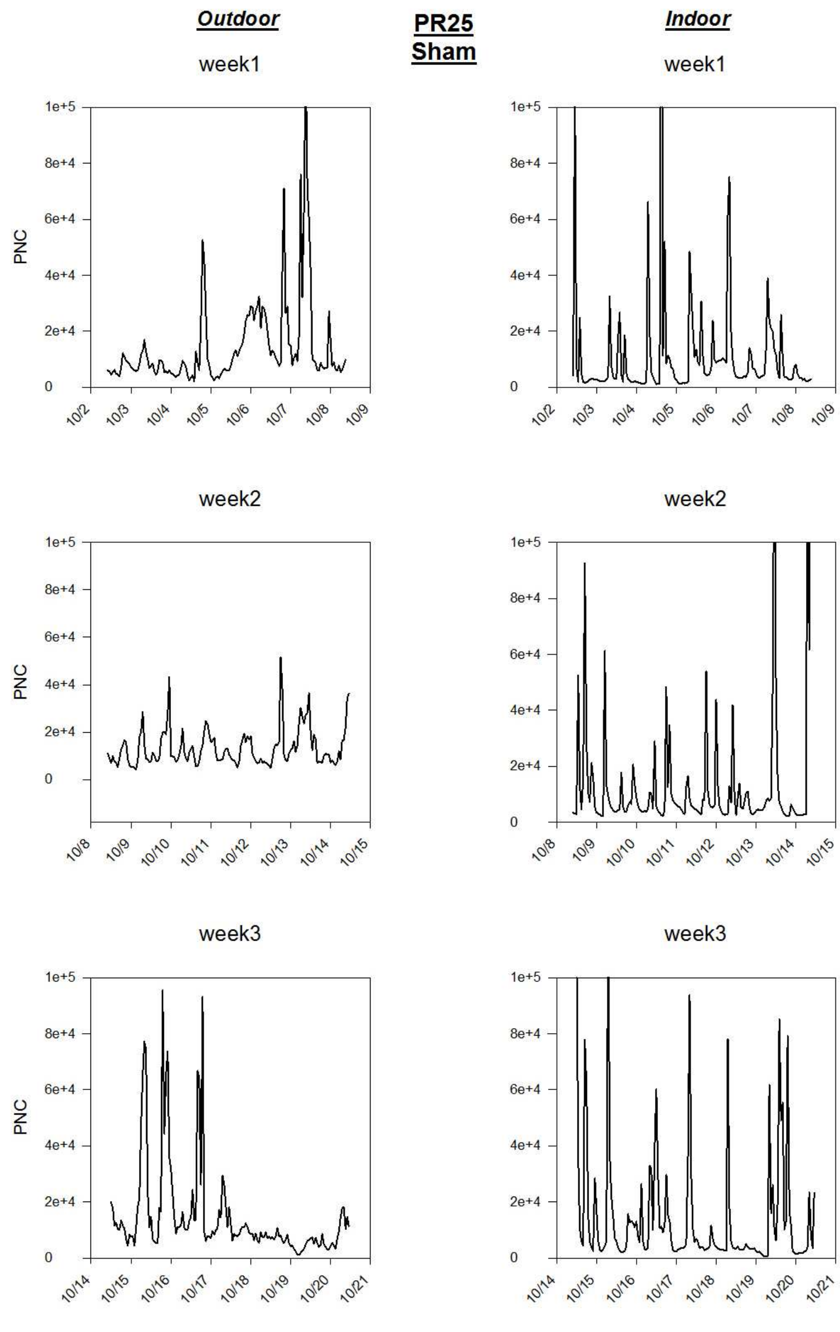


Figure 79. Weekly PNC variations for PR25 during sham filtration

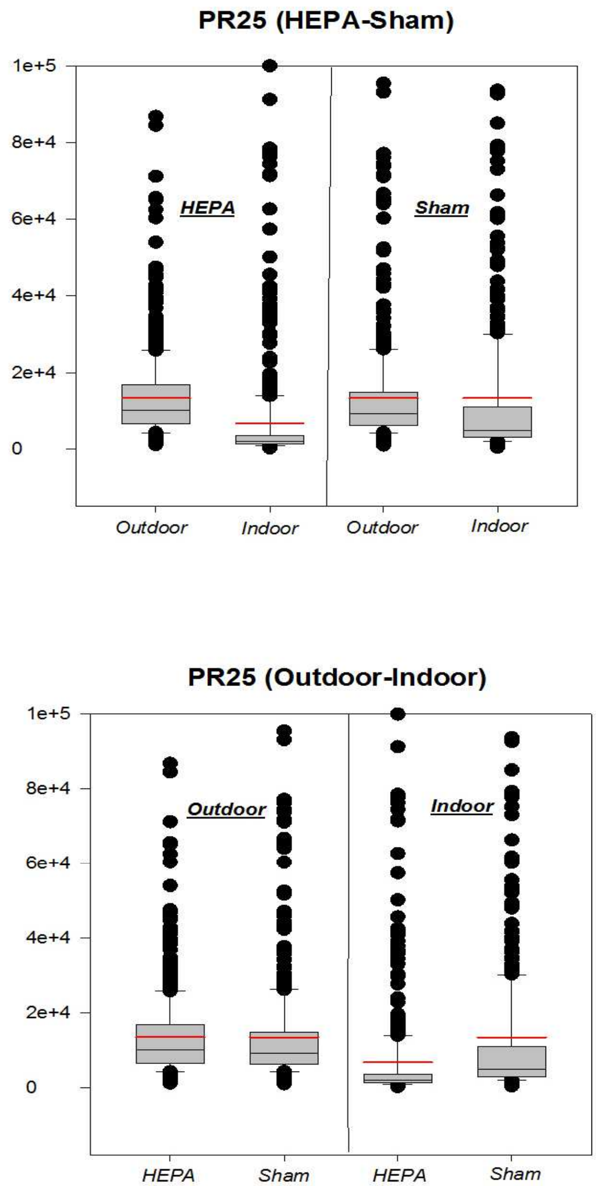


Figure 80. Boxplot for PNC variations for PR25 during HEPA and sham filtration

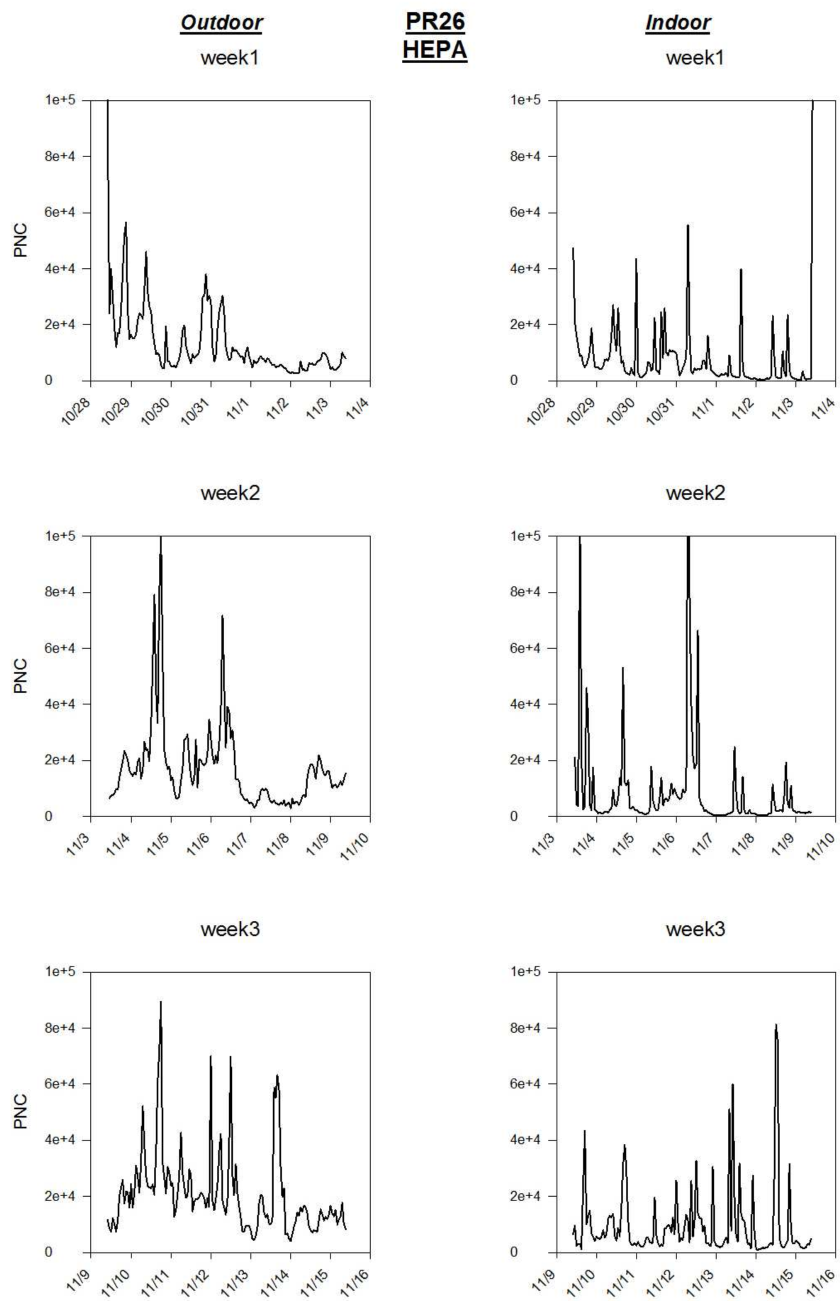


Figure 81. Weekly PNC variations for PR26 during HEPA filtration

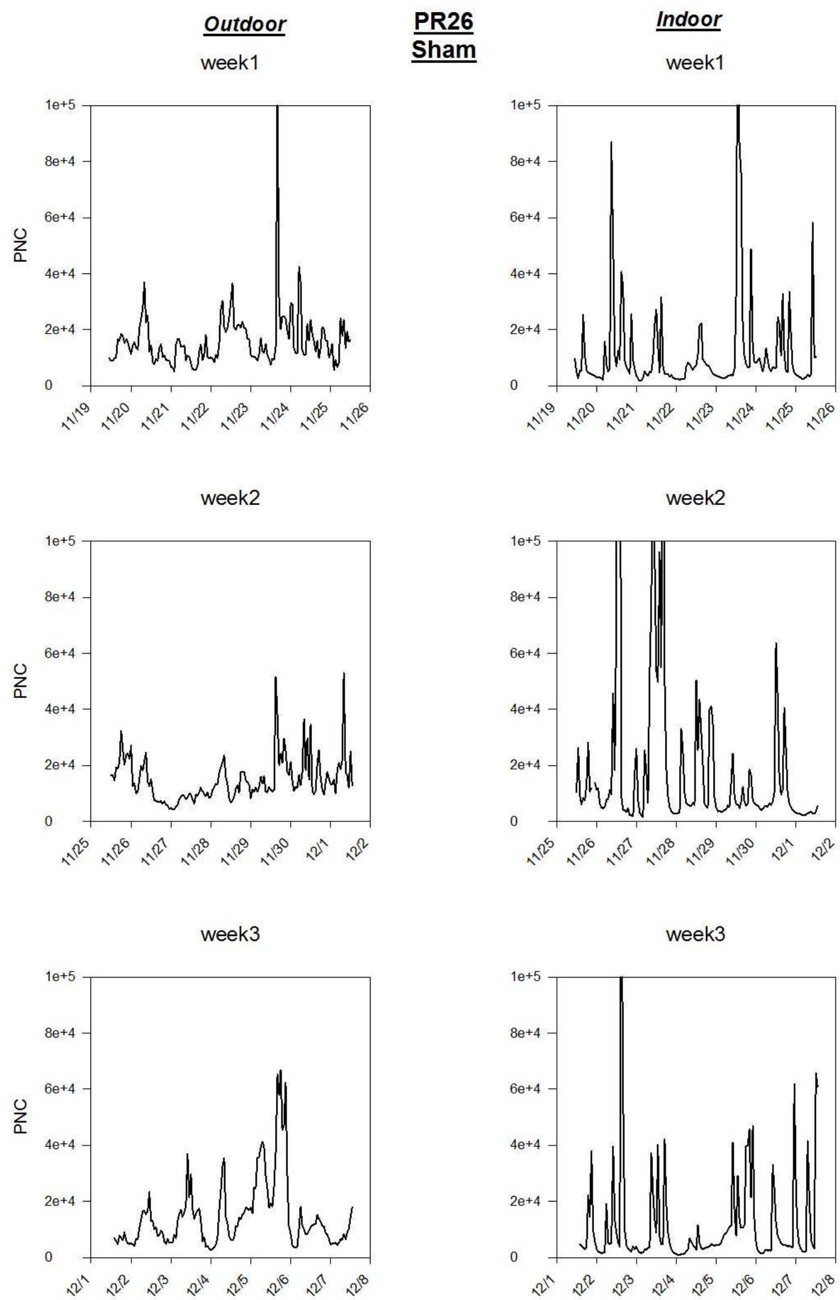


Figure 82. Weekly PNC variations for PR26 during sham filtration

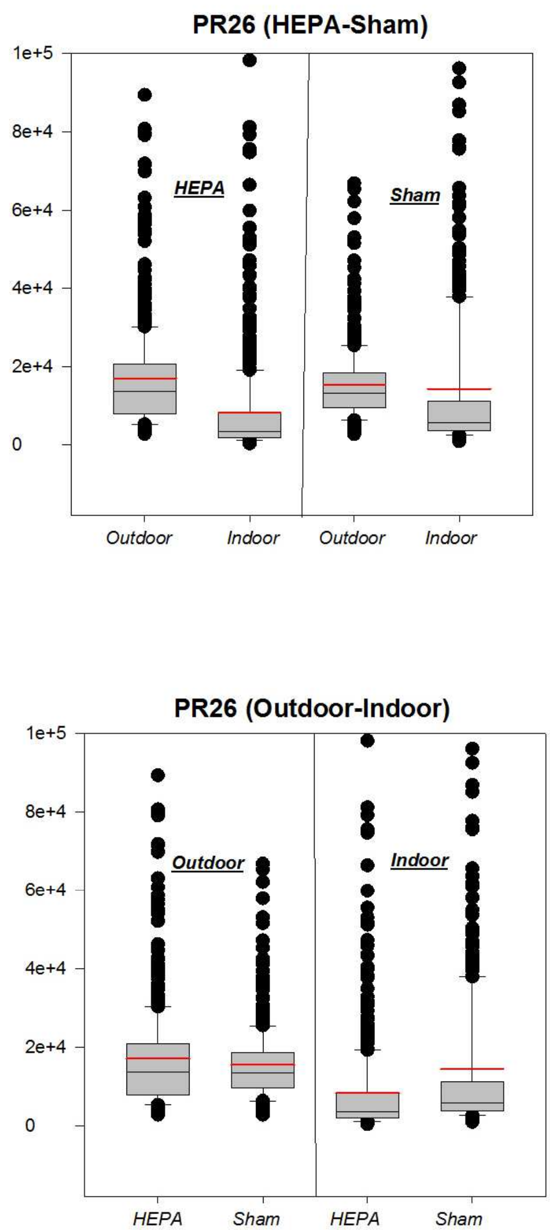


Figure 83. Boxplot for PNC variations for PR26 during HEPA and sham filtration